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THE DIURNAL PERIODICITY OF EARTHQUAKES

CHARLES DAVISON
Cambridge, England

ABSTRACT

Though non-instrumental records of earthquakes give an apparent nocturnal maximum, it is shown that, for several regions in which earthquakes are weak or moderately strong, there is a real diurnal period, with its maximum about midnight. The instrumental records obtained in Japan and Italy and at various seismological observatories are examined, and it is shown that the maximum epoch of the diurnal period usually falls about noon or midnight, and that the noon maximum of the diurnal period is associated, as a rule, with a summer maximum of the annual period, and the midnight maximum of the former with a winter maximum of the latter. It is suggested that the noon and summer maxima occur in earthquakes caused by an elevation of the crust, and the midnight and winter maxima in those caused by a depression of the crust. It is noticed that the midnight and winter maxima prevail in regions in which the earthquakes are of slight or moderate intensity, and the noon and summer maxima in those visited by the most destructive shocks. In the after-shocks of great earthquakes, the maxima epoch are suddenly reversed, usually from near noon to near midnight, and the duration of the reversal varies from about a week to a year or more.

In several earlier papers, the writer has considered the diurnal periodicity of earthquakes.[1] In this study, the records previously used, together with others subsequently published, have been examined.

The method employed is similar to that adopted in the writer's other papers. The numbers of earthquakes occurring during each hour of the day are counted, and 12-hourly means are taken for

[1] *Phil. Mag.*, Vol. XLII (1896), pp. 463–76; Vol. XLI (1921), pp. 908–16; Vol. XLIII (1922), pp. 878–85.

each of the 24 numbers. For instance, let us suppose that the numbers of earthquakes felt during successive hours are:

	0–1	1–2	2–3	3–4	4–5	5–6	6–7	7–8	8–9	9–10	10–11	11–12
A.M.	104	163	215	250	259	250	177	162	171	199	246	300
P.M.	346	373	371	336	277	200	123	63	29	25	54	100

These numbers are represented by the continuous curve in the accompanying figure, from which it will be seen that there are two maxima of frequency: one at 4–5 A.M.; the other, and more important, at 1–2 P.M.

If the numbers from 7–8 P.M. to 6–7 A.M. are added together, the 12-hourly mean (1,688) is obtained corresponding to the middle of this interval of 12 hours, that is, to the end of the hour 0–1 A.M., or 1 A.M., the division by 12 being unnecessary. Proceeding in this way, the 12-hourly means for the whole day are:

A.M.	1,688	1,788	1,930	2,104	2,296	2,496	2,738	2,948	3,104	3,190	3,208	3,158
P.M.	3,104	3,004	2,862	2,688	2,496	2,296	2,054	1,844	1,688	1,602	1,584	1,634

The sum of the numbers for 0–1 A.M. and 0–1 P.M., or 1,888+3,104, or 4,792, is the total number of earthquakes. Dividing each of the 12-hourly means by the average, 4,792÷2, or 2,396, the 12-hourly means referred to the mean hourly number as unity are obtained. These are:

A.M.	.70	.75	.81	.88	.96	1.04	1.14	1.23	1.30	1.33	1.34	1.32
P.M.	1.30	1.25	1.19	1.12	1.04	.96	.86	.77	.70	.67	.66	.68

These means are, however, affected by the process of smoothing; and, to obtain the final hourly means, the difference between each of the foregoing numbers and unity must be multiplied by the factor 1.575, giving for the final results:

A.M.	.53	.61	.70	.81	.94	1.06	1.22	1.36	1.47	1.52	1.54	1.51
P.M.	1.47	1.39	1.30	1.19	1.06	.94	.78	.64	.53	.48	.46	.49

This series of numbers is represented by the broken line in Figure 1, showing that the *maximum-epoch* of the diurnal period is at the end of the hour 10–11 A.M., i.e., at 11 A.M. The ordinate of the curve at this point, known as the *amplitude*, is .54.

The given series of numbers was obtained by taking the sum of two series, one representing a diurnal period and the other a semi-diurnal period. The latter is not of concern at present; but it may be noted that, in order to obtain the semi-diurnal period, the num-

bers of earthquakes for 0–1 A.M. and 0–1 P.M., and so on, are added together, and 6-hourly means taken of the 12 numbers. The process is the same as before, with the exception of the fact that the factor giving the final values of the means is 1.589. The resulting means are represented by the dotted line in the figure, showing that the maximum-epochs of the period are at 3 A.M. and 3 P.M., and the amplitude .49. The sum of corresponding ordinates of the broken line and dotted line gives the ordinate of the continuous curve. Thus, the diurnal variation represented by the latter curve is com-

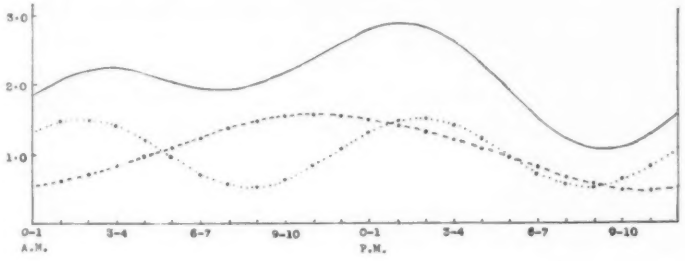


FIG. 1

pounded of two periods of durations—24 hours and 12 hours, respectively.

Owing to the variable conditions under which observers live during the day, the most useful records are those provided by instruments. In the first section the writer has, however, considered several personal records.

NON-INSTRUMENTAL RECORDS

Great Britain.—The hour of occurrence is known for 909 earthquakes from 1750 to 1916.[2] Of these, 337 belonged to centres near Comrie in Perthshire and 191 to centres near Menstrie in Clackmannanshire. These two series are somewhat similar and, in their frequent occurrence during short intervals of time, differ from all other earthquakes in the country. The numbers of shocks felt dur-

[2] *History of British Earthquakes* (1924), pp. 15–34.

ing each of the 24 hours in Great Britain without Comrie and Menstrie were:

A.M.	13	34	21	23	18	17	14	8	14	12	16	13
P.M.	4	15	12	12	18	10	14	12	20	15	18	28

In the Comrie and Menstrie districts together, the hourly numbers were:

A.M.	19	38	37	29	24	25	21	18	18	25	11	15
P.M.	11	29	24	22	26	23	11	18	14	21	18	31

Thus, both series show two pronounced maxima: one from 11 to 12 P.M., and the other from 1 to 2 A.M. There can be little doubt that these apparent maxima are due in great part to unusually favourable conditions of observation, as many persons are awake and resting quietly at these times.

The analysis of the records is given in Table I. The maximum epoch thus falls shortly after midnight. That the diurnal periodicity

TABLE I

Region	No. of Shocks	Epoch	Amplitude
Great Britain	910	1 A.M.	.25
Great Britain, without Comrie and Menstrie	381	0½ A.M.	.33
Comrie and Menstrie	529	4 A.M.	.24

TABLE II

Region	Intensity	No. of Shocks	Epoch	Amplitude
Great Britain	9–4	228	12 MIDN.	.28
	about 3	407	about 3½ A.M.	.27
Great Britain, without Comrie and Menstrie	9–4	125	12 MIDN.	.44
	about 3	86	10 P.M.	.41
Comrie and Menstrie	8–4	103	about 9 P.M.	.35
	about 3	321	4 A.M.	.30

is not, however, entirely due to the conditions of the observer seems clear if we classify the earthquakes according to their intensity. Owing to their small number, it is only possible to arrange them in two classes.

As few persons would not be awakened by a shock of intensity 4, it would seem that there must be a real diurnal period in British earthquakes, with its maximum about midnight, though with its amplitude possibly increased by the favourable conditions of the observer.

In the annual period for the same interval of time, the maximum epoch falls at the end of December, the amplitude being .25.

Zante.—The results given in Table III are founded on the valuable lists of Greek earthquakes compiled by Professor D. Egini-

TABLE III

	No. of Shocks	Epoch	Amplitude
All earthquakes	3,174	2 A.M.	.32
Intensities 9–4	202	1 A.M.	.22
Intensity 3	1,776	2 A.M.	.33

tis for the years 1893–1914.[3] In these twenty-two years, the times of 3,174 earthquakes in Zante were recorded, the numbers during the 24 hours being:

A.M.	188	175	213	159	157	162	139	136	87	63	114	104
P.M.	115	125	114	115	108	86	123	114	152	129	102	176

Thus, as in Great Britain, there are two nocturnal maxima, though in Greece the maximum before or about midnight is less pronounced.

The interval covered by the preceding table includes two great earthquakes, those of 1893, January 31, and April 17, with their attendant after-shocks. Excluding the years 1893 and 1894, there were 2,146 shocks, with the maximum at 2 A.M. and the amplitude .38. During the same interval, the maximum epoch of the annual period occurred at the end of January, the amplitude being .30.

The earthquakes during the years 1893–1914 were so numerous that it is possible to draw up a similar table for the separate months. The monthly numbers of shocks range from 161 to 396, and the epoch falls between midnight and 2 A.M., with one exception at 10 P.M. and another at 5 A.M. It is interesting to notice that the ampli-

[3] *Athènes Obs. Nat. Ann.*, Vol. II (1900), pp. 189–346; Vol. III (1901), pp. 336–75; Vol. IV (1906), pp. 489–551; Vol. V (1910), pp. 560–92; Vol. VI (1912), pp. 304–33; Vol. VII (1916), pp. 374–427.

tude is subject to a marked annual period, with its maximum at the end of October and an amplitude of .52.

Switzerland.—The following results depend on the lists of earthquakes felt during the years 1914–28,[4] in which the times of 667 earthquakes were recorded by the Swiss Earthquake Commission. The hourly numbers are:

A.M.	44	36	48	51	43	36	28	18	13	15	22	14
P.M.	21	21	21	28	26	9	19	19	18	28	43	46

There are thus the usual maxima just before midnight and a few hours later. Table IV therefore leads to the same conclusions as

TABLE IV

	No. of Shocks	Epoch	Amplitude
All earthquakes	667	1 A.M.	.50
Intensities 8–4	261	2 A.M.	.32
Intensity 3	222	12 MIDN.	.58

those for Great Britain and Zante. During the same interval, the maximum epoch of the annual period occurred at the end of January, the amplitude being .35.

Philippines, etc.—Similar results for a few well-known earthquake regions[5] are given in Table V.

TABLE V

Region	Interval	No. of Shocks	Epoch	Amplitude	Epoch of Annual Period
Philippines	1866–89	827	10 A.M.	.08	July
California	1851–87	557	1 A.M.	.32	Oct.
New Zealand	1868–90	505	2½ A.M.	.30	May
Atacama (Chile)	1906–8	341	3 A.M.	.25	.....

[4] *Jahrb. des Schweiz. Erdbeben-dienstes* (1914–28).

[5] M. Saderra Masò, *La Seismologia en Filipinas* (Manila, 1895), pp. 40–50, 69–79, and *Catalogue of Violent and Destructive Earthquakes in the Philippines, 1599–1909* (Manila, 1910); E. S. Holden, *List of Recorded Earthquakes in California, etc., 1887*, pp. 78; Sir J. Hector, *Austral. Assoc. Trans.*, Vol. III (1891), pp. 507–20; F. de Montessus de Ballore, *Chile Serv. Sismol. Bol., 1906–08.*

JAPAN

In the first of the following tables, the results depend entirely on instrumental records,[6] with the exception of the first month at Kumamoto.

TABLE VI

Station	Interval	No. of Shocks	Epoch	Amplitude	Epoch of Annual Period
Tokyo	1886–1902	1,962	12 NOON	.08	May
Tokyo, sensible earthquakes	1887, Sept.–1889, July	209	0½ P.M.	.38	.....
Kumamoto	1890–99	1,014	11 A.M.	.19	.....
Oita	1887–99	237	11 A.M.	.39	.....
Hikone	1894–99	245	10 A.M.	.14	.....

TABLE VII

Station	Interval	No. of Shocks	Epoch	Amplitude	Epoch of Annual Period
Sapporo	1876–81–99	153	11 P.M.	.23	Dec.
Hakodate	1873–95–99	301	10 P.M.	.25	Dec.
Akita	1883–94–99	285	10 P.M.	.14	Nov.
Tsu	1889–99–99	266	9 P.M.	.25	Jan.
Kochi	1883–93–99	86	about 0½ A.M.	.25	Jan.
Miyako	1883–96–99	704	3 P.M.	.16	May
Yamagata	1889–94–99	197	2 P.M.	.35	June
Ishinomaki	1886–91–99	1,034	3 P.M.	.27	Aug.
Fukushima	1889–95–99	857	3 P.M.	.11	Apr.
Utsunomiya	1984–* –99	492	2 P.M.	.14	July
Wakayama	1879–88–99	403	about 5½ P.M.	.11	May

* There is some misprint in the dates. Omori gives the date of beginning of the instrumental record as July, 1893.

In Table VII, the records were in part instrumental, starting from the second year mentioned under the heading "interval." The hourly numbers of shocks are those given by Omori in his memoir on the annual and diurnal variations of seismic frequency in Japan,[7] with

[6] *Brit. Assoc. Rep.*, *1886*, pp. 414–15; *1887*, pp. 212–13; *1888*, pp. 434–37; *1889*, pp. 295–96; *1890*, pp. 160–62; *1891*, pp. 123–24; *1892*, pp. 93–95; *1893*, pp. 214–15; *1895*, pp. 82–83, 114–15; *1897*, pp. 133–37; *1898*, pp. 189–91; *1899*, pp. 189–91; *Brit. Assoc. Seis. Com. Circ.*, Vol. I, pp. 29–30, 90–92, 142–44, 223–25; *Imp. Earthq. Inv. Com. Publ.*, No. 8 (1902), pp. 1–94, and No. 11 (1902), pp. 3–6.

[7] F. Omori, *Imp. Earthq. Inv. Com. Publ.*, No. 8 (1902), pp. 1–94.

the exception of the two stations—Akita and Tsu. In Omori's table, the numbers of shocks are given for each hour during each month. The numbers of shocks for 5–6 P.M. and 6–7 P.M. in August are unusually large, as they include after-shocks of the Riku-U earthquake of 1891, August 31. Omori omits the August numbers for the hours mentioned with the exception of one for each hour. In obtaining the results for Akita, all the numbers for August are here omitted. Similarly, for Tsu, all the October numbers have been omitted, as they include large numbers of after-shocks of the Mino-Owari earthquake of 1891, October 28, especially during the hours 6–7 and 7–8 A.M.

In Table VIII, the earthquakes of submarine origin are those recorded in Milne's catalogue for 1885–92 and depend in part on per-

TABLE VIII

Region	No. of Shocks	Epoch	Amplitude	Epoch of Annual Period
Japan, submarine earthquakes	2,469	1 A.M.	.08	Dec.
Mount Tsukuba, sensible earthquakes	171	4 P.M.	.20	.....
Mount Tsukuba, insensible earthquakes	316	3 A.M.	.17	.....

sonal observations. The distances of the epicentres from land range from 5 to 40 miles, clustering for the most part in the neighbourhood of 10 miles. The earthquakes at Mount Tsukuba during 1905 were recorded instrumentally.[8]

Thus, at the stations included in Table VI, the maximum epoch occurs at or near noon. In Table VII, it falls at about midnight in the first five stations and at about noon in the last six, and it is interesting to notice that the midnight maximum of the diurnal period is associated with a winter maximum of the annual period, and the noon maximum of the former with a summer maximum of the latter.

ITALY

Professor A. Cavasino has made a valuable study on the frequency and distribution of Italian earthquakes during the forty

[8] *Ibid.*, No. 22 A (1908), pp. 1–39.

years 1891–1930.[9] In this, he gives a table (p. 214) of the numbers of earthquakes felt in 2-hourly intervals.[10] The 2-hourly numbers are as follows: 1,686, 1,913, 1,578, 1,300, 1,052, 1,115, 1,051, 1,108, 1,058, 1,046, 1,263, and 1,462, thus showing only one prominent maximum during the hours 2–4 A.M.[11] The analysis of these figures gives (number of shocks 15,632) the epoch at 2 A.M. and the amplitude .29. For the same earthquakes, the epoch of the annual period is at the end of June and the amplitude .05.

For the separate months, the epoch occurs at 12 midnight in January, 4 A.M. in July, and 2 A.M. in each of the other months.

TABLE IX

Intensity	No. of Shocks	Epoch	Amplitude
9–7	28	1½ P.M.	.46
6	64	12 MIDN.	.19
5	229	2 A.M.	.36
4	543	3 A.M.	.24
3	696	2 A.M.	.44

TABLE X

Intensity	No. of Shocks	Epoch	Amplitude
3, 2	57	about 8 A.M.	.36
1	169	9 P.M.	.19

The variation of amplitude is subject to a well-marked annual period, the maximum being in the middle of January and the amplitude .29.

Table IX relates to sensible earthquakes or macroseisms during the ten years 1918–27, the intensities being given in the Mercalli scale. Table X contains the results, as regards intensity, obtained from Milne's catalogue of destructive earthquakes (1756–1898), the

[9] *Ital. Soc. Sism. Boll.*, Vol. XXX (1931–32), pp. 195–216.

[10] The table depends on personal observations, supported by instrumental records.

[11] If the hourly numbers for Great Britain and Zante are grouped in 2-hourly intervals, they show only one prominent maximum, shortly after midnight. Those for Switzerland give two maxima—one just before, the other shortly after, midnight.

degrees 3, 2, and 1 corresponding roughly with the degrees 10, 9, and 8 of the Mercalli scale.

The preceding results may be compared with those in Table XI which gives the elements obtained from microseisms recorded instrumentally at Italian stations (1918–24), the annual epoch in both cases being in July, with amplitudes of .25 and .41.

TABLE XI

Recorded at:	No. of Shocks	Epoch	Amplitude
Five or more stations	345	2 P.M.	.14
One station only	1,674	1 A.M.	.06

In a paper published in 1889,[12] M. de Montessus de Ballore gave the hourly numbers of shocks at various Italian observatories. The results deduced from this list are given in Table XII.

TABLE XII

Station	No. of Shocks	Epoch	Amplitude
Acireale	384	3 P.M.	.55
Bologna, etc.	636	1½ P.M.	.61
Cascia	505	2 A.M.	.35
Corleone	584	12 MIDN.	.54
Rocca di Papa	389	3 P.M.	.44
Rome	2,346	1 P.M.	.60
Velletri	1,491	12 NOON	.43
Verona	720	11½ A.M.	.44
Vesuvius	547	12 NOON	.41

The Italian catalogues thus agree in leading to the following conclusions: (1) for the most destructive earthquakes the daily maximum occurs at or about noon, and (2) for semi-destructive and weaker earthquakes at or about midnight.

VARIOUS SEISMOLOGICAL STATIONS

Table XIII gives results deduced from the registers collected by the Seismological Committee of the British Association, ending as a

[12] *Arch. Sci. Phys. Nat.*, Vol. XXII (1889), pp. 409–30.

rule with the year 1912. The time at which the preliminary tremors were first recorded is taken as the time of occurrence of the earthquake, and thus the maximum epoch may be retarded, but by an amount that is certainly less than the time required by the tremors to travel from the most distant origin. In the last column is given the epoch of the annual period, the end of the month mentioned being implied.

TABLE XIII

Station	No. of Shocks	Epoch	Amplitude	Epoch of Annual Period
Shide	1,995	11 A.M.	.13	May
Kew	1,251	12 NOON	.32	July
Paisley	603	12 NOON	.35	July
Valetta	516	about 10 A.M.	.20	.....
Bombay	693	2 P.M.	.19	Jan.
Madras	870	about 3 P.M.	.11	May
Batavia	1,292	11 A.M.	.16	June
Tokyo	934	1 P.M.	.43	May
Cape of Good Hope	626	12 NOON	.13	Mar.
Trinidad	416	about 1 P.M.	.79	May
Toronto	1,218	1½ P.M.	.13	Jan.
San Fernando	1,264	1 A.M.	.28	Feb.
Baltimore	444	about 11 P.M.	.19	.....
Cordova (Arg.)	814	12 MIDN.	.57	May
Calcutta	832	5 P.M.	.22	.....
Christchurch (N.Z.)	474	4 P.M.	.32	Mar.
Honolulu	860	4 P.M.	.30	May

In some of the records, it is possible to make a rough classification of earthquakes according to intensity. The earthquakes in the diagrams of which a maximum can be clearly distinguished are not of necessity strong, but among them are included all strong earthquakes. Those which contain no marked maximum are, as a rule, of much less intensity. These two classes of earthquakes are denoted by the letters *A* and *B* in Table XIV.

Table XV contains the results obtained from the records at a few other observatories.[13]

[13] E. van Everdingen, *Seis. Regis. in De Bilt, 1918–29;* A. Hée, *Matér. pour l'Étude des Calamités,* No. 28 (1932), pp. 291–337; H. O. Wood, *Univ. of Calif. Publ. Seis. Sta. Bull. 1912–20;* M. Saderra Masò, *La Seismologia en Filipinas, 1895,* pp. 100–103.

From Tables XIII–XV we may conclude:

1. At thirteen stations, the maximum occurs at or near noon; at six, at or near midnight; and, at three others, in the afternoon.

2. As in Japanese stations referred to on preceding pages, a diurnal maximum about noon is frequently associated with an annual maximum in the summer months, and a diurnal maximum about midnight with an annual maximum in winter. For the fore-

TABLE XIV

Station	A		B	
	Epoch	Amplitude	Epoch	Amplitude
Shide	11 A.M.	.05	0½ P.M.	.39
Kew	about 1 P.M.	.16	1 P.M.	.43
Cape of Good Hope	1 P.M.	.17	12 NOON	.25
Edinburgh	11 A.M.	.08	10 P.M.	.16
San Fernando	about 11 A.M.	.11	1 A.M.	.77
Toronto	about 0½ A.M.	.16	1½ P.M.	.30
Victoria, B.C.	about 11 P.M.	.17	10 A.M.	.11
Cordova (Arg.)	5 P.M.	.23	0½ A.M.	.90

TABLE XV

Station	Interval	No. of Shocks	Epoch	Amplitude	Epoch of Annual Period
De Bilt	1909–29	6,883	10 P.M.	.09	July
Bouzaréa (Alg.)	1912–31	242	2 P.M.	.47	about Aug.
Berkeley (Cal.)	1913–19	541	2 A.M.	.22	July
Lick Observatory (Cal.)	1913–19	880	9 P.M.	.80	July
Manila	1869–89	208	11 A.M.	.30	Aug.

going stations, this holds for both hemispheres; but the relation is by no means constant.

3. At three stations, the epochs for strong and weak earthquakes agree closely. At four others, the epochs are approximately reversed. There is also a reversal in epoch for the earthquakes recorded at Manila (Table XV) and the destructive earthquakes in the Philippines (Table V).

AFTER-SHOCKS OF EARTHQUAKES

This section relates to the diurnal periodicity of the after-shocks of 7 great earthquakes in Japan and of 5 others in Italy, Greece, and New Zealand.

KUMAMOTO EARTHQUAKE: 1889, JULY 28

The principal earthquake occurred at 11.49 P.M. Professor Omori gives the hourly numbers of earthquakes recorded at Kumamoto from July 31 to August 13,[14] which leads to the following results (148 shocks): epoch at 12 midnight, amplitude of .55.

TABLE XVI

Station	Interval	No. of Shocks	Epoch	Amplitude
Gifu	Oct. 29–Nov. 2	808	12 MIDN	.22
	Nov. 3–10	447	1 A.M.	.20
	Nov. 11–Dec. 31	839	12 MIDN.	.32
	1892	865	12 MIDN.	.19
	1893	272	2 P.M.	.11
	1894–99	882	5 P.M.	.11
Nagoya	Oct. 29–Nov. 2	416	3 A.M.	.38
	Nov. 3–10	154	1 A.M.	.39
Rect. 1457	Nov. 1–5	250	0½ A.M.	.35
	Nov. 6–10	116	1 A.M.	.54
	Nov. 11–20	207	1 A.M.	.68
	Nov. 21–30	118	2 A.M.	.69
	Dec.	290	.....	.....
	1892	98	2 A.M.	.49

MINO-OWARI EARTHQUAKE: 1891, OCTOBER 28

The earthquake occurred at 6.37 A.M. The after-shocks were recorded at Gifu from 1.55 P.M. on the same day, and at Nagoya from 1.10 P.M.[15] In his catalogue of earthquakes recorded in Japan during the years 1885–92,[16] Professor Milne gives the approximate position of the epicentre of every after-shock beginning on November 1. He divides the whole country into rectangles by lines of latitude and longitude ½ of a degree apart. The rectangle in which most epicentres lie is that numbered by him 1,457, its centre being in altitude 35°15′ N., longitude 136°55′ E.

[14] *Tokyo Imp. Univ. Coll. Sci. Jour.*, Vol. VII (1894), p. 157.

[15] *Ibid.*, pp. 178–89. [16] *Japan Seis. Jour.*, Vol. IV (1895), pp. 134–234, 302–53.

KAGOSHIMA EARTHQUAKE: 1893, SEPTEMBER 7

The earthquake occurred at about 2.46 A.M., and the hourly numbers of after-shocks recorded at Chiran[17] from September 8 to 21 give the following results (233 shocks): epoch at 4 A.M., amplitude of .22.

HOKKAIDO EARTHQUAKE: 1894, MARCH 22

The earthquake occurred at 7.56 P.M., and the after-shocks were recorded at Nemuro, 75 miles from the epicentre.[18]

KWANTO EARTHQUAKE: 1923, SEPTEMBER 1

The earthquake occurred at 11.59 A.M. A list of the after-shocks sensible in Tokyo from September 1 to October 1 is given by Imamura

TABLE XVII

Interval	No. of Shocks	Epoch	Amplitude
March 23–31	296	7½ A.M.	.30
April–December	321	6½ A.M.	.17
1895	125	about 1 A.M.	.22
1896–99	250	11 A.M.	.16

and Hasegawa,[19] and another list of all those instrumentally recorded in the same city is given by T. Yasuda.[20] Deducting the numbers in the former table from the numbers for the same intervals in the latter, the number of shocks recorded in Tokyo that were imperceptible to human beings are obtained.[21]

[17] *Tokyo Imp. Univ. Coll. Sci. Jour.*, *op. cit.*, p. 194.

[18] Omori, *Imp. Earthq. Inv. Com. Publ.*, No. 7 (1902), pp. 35–51.

[19] *Ibid.*, Vol. XI (1828), pp. 72–93.

[20] *Ibid.* (in Jap.), No. 100 A (1925), pp. 261–310.

[21] The sums of the totals of perceptible and imperceptible shocks for the first three intervals differ from those in the first three lines of Table XVIII. The reason is that, for the hour 8–9 during September 2–10, Imamura and Hasegawa give 13 perceptible shocks, while Yasuda gives only 8 shocks of all intensities. Of these entries, only 2 correspond to the same shocks, leaving 6 imperceptible shocks for this hour. Similar but smaller differences exist for the house 4–5 in the interval September 11–20, and for the hours 7–8, 14–15, and 17–18 during the interval September 21–30.

TAZIMA EARTHQUAKE: 1925, May 23

The earthquake occurred at 11.11 A.M., and the after-shocks were recorded without interruption at Toyooka, 7 miles south of the epicentre.[22]

TABLE XVIII

Earthquakes	Interval	No. of Shocks	Epoch	Amplitude
All earthquakes	Sept. 2–10	804	4 P.M.	.32
	Sept. 11–20	197	1 P.M.	.32
	Sept. 21–30	76	7 A.M.	.25
	Sept. 2–30	1,077	3 P.M.	.24
	Oct.–Nov.	182	4 A.M.	.39
	Dec.–Jan.	306	3½ A.M.	.17
Perceptible in Tokyo	Sept. 2–10	386	11 P.M.	.16
	Sept. 11–20	98	11½ P.M.	.28
	Sept. 21–30	47	12 NOON	.44
Imperceptible in Tokyo	Sept. 2–10	429	3 P.M.	.60
	Sept. 11–20	102	12 NOON	.71
	Sept. 21–30	34	12 MIDN.	.46

TABLE XIX

Interval	No. of Shocks	Epoch	Amplitude
May 24–26	128	2 A.M.	.39
May 27–28	56	about 1½ A.M.	.17
May 29–June 2	52	about 11 A.M.	.43
June 3–17	100	0½ P.M.	.69

TANGO EARTHQUAKE: 1927, MARCH 7

The earthquake occurred at 6.27 P.M., and the after-shocks were recorded at Maiduru from March 11 and at Kinosaki and Inemura from March 12.[23] A strong after-shock occurred at 6.7 A.M. on April 1 and was followed, mostly within a few hours, by 191 after-shocks on the same day.

From observations made at the preceding stations Mr. N. Nasu was able to determine the focal depths of 438 after-shocks from 1927,

[22] A. Imamura, *Imp. Earthq. Inv. Com. Bull.*, Vol. X (1892), pp. 97–107.

[23] N. Nasu, *Earthq. Res. Inst. Bull.*, Vol. VI (1929), pp. 300–31; Vol. VII (1930), pp. 148–51.

March 14, to 1928, August 31. The maximum epoch of these after-shocks occurred at 3 A M., the amplitude of the period being .24. The mean depth of all the foci was 14.9 kilometers or 9.3 miles. In a previous paper,[24] the writer has shown that there was a marked 42-minute period in the depth of the foci, the epoch from March 12 to 31 being at 21 minutes and the amplitude .06. The diurnal period is less distinctly marked, its amplitude being only .03, but its peak occurred

TABLE XX

Interval	No. of Shocks	Epoch	Amplitude
Mar. 12–13	92	2 P.M.	.35
Mar. 14–17	108	2½ A.M.	.20
Mar. 18–21	179	about 1 A.M.	.35
Apr. 2–30	334	3 A.M.	.32
May–Aug.	286	about 4 A.M.	.13
1927, Sept.–1928, July	135	1 A.M.	.38

at 3 A.M., or at the same hour as that of the diurnal period of the after-shocks with known focal depths.

MESSINA EARTHQUAKE: 1908, DECEMBER 28

The earthquake occurred at 5.20 A.M. After-shocks were recorded the same day at 5.36 A.M. at Mileto, 5.44 A.M. at Catania, and 9.19 A.M. at Mineo. At Messina, the records began on January 1.[25] In the *Notizie* issued by the Central Office of Meteorology and Geodynamics, many earthquakes are specially denoted as after-shocks of the Messina earthquake. In Table XXI these are inserted under the title "General."

MARSICA EARTHQUAKE: 1915, JANUARY 13

The earthquake occurred at 7.53 A.M., and the after-shocks were recorded at Rocca di Papa, 47 miles from the epicentre.[26]

LOCRIS EARTHQUAKES: 1894, APRIL 20 AND 27

The earthquakes occurred at 6.52 P.M. on April 20 and 9.30 P.M. on April 27. The shocks were recorded at the observatory of

[24] *Amer. Seis. Soc. Bull.*, Vol. XXIII (1933), p. 68.

[25] *Itl. Soc. Sism. Boll.*, Vol. XV, Part 2 (1911), pp. 566–639; Vol. XVI, Part 2 (1912), pp. 1–50.

[26] Cavasino, *Itl. Soc. Sism. Boll.*, Vol. XIX (1915), pp. 236–91.

Athens, about 60 miles from the epicentre. During the interval April 21–July 30, 60 shocks were recorded,[27] giving the maximum epoch at 3 A.M. and the amplitude .63.

TABLE XXI

Record	Interval	No. of Shocks	Epoch	Amplitude
General	1908, Dec. 29—1909, Jan. 31	123	12 MIDN.	.44
	1909, Feb.–June	71	2 A.M.	.16
Catania	1907–8, Dec. 27	211	11 A.M.	.33
	1908, Dec. 29—1909, Jan. 31	101	2½ A.M.	.39
	1909, Feb.–June	62	5½ A.M.	.41
Messina	1907–8, Dec. 27	258	9 A.M.	.25
	1909, Jan.	123	12 MIDN.	.52
	Feb.–June	374	2 A.M.	.27
	July–Dec.	380	1½ A.M.	.08
	1910	293	10 A.M.	.17
Mileto	1907–8, Dec. 27	156	about 9 A.M.	.22
	1908, Dec. 29—1909, Jan. 31	87	2 A.M.	.38
	1909, Feb.–June	77	11 P.M.	.39
Mineo	1908, Jan. 1–Dec. 27	63	10 A.M.	.58
	1908, Dec. 29—1909, Dec. 31	120	11 P.M.	.....
	1910–11	79	6½ A.M.	.58

TABLE XXII

Interval	No. of Shocks	Epoch	Amplitude
Jan. 14–18	315	6 A.M.	.24
Jan. 19–23	77	6 A.M.	.22
Jan. 24–31	79	.....	.....
Feb.	201	12 NOON	.16
Mar.	116	about 4½ A.M.	.22
Apr.	98	4 P.M.	.32
May–June	135	4 A.M.	.20

MURCHISON (N.Z.) EARTHQUAKE: 1929, JUNE 16

The earthquake occurred at 10.26 A.M. and the shocks were recorded at Wellington.[28] From June 23 to August 31, there were 229 shocks, the epoch being at 10 P.M. and the amplitude .16.

[27] Eginitis, *Athènes Obs. Nat. Ann., op. cit.*, pp. 217–31.

[28] C. E. Adams, *Wellington N.Z. Dom. Obs. Bulls. E 21, E 22.*

HAWKE'S BAY (N.Z.) EARTHQUAKE: 1931, FEBRUARY 3

The earthquake occurred at 10.26 P.M. From 1931, February 4, to 1932, June 28, there were 74 prominent after-shocks,[29] giving the epoch at 12 MIDT. and the amplitude .25.

These results lead to the following conclusions:

1. Immediately after the principal earthquake, the epoch of the daily period is suddenly reversed, usually from near noon to near midnight.

2. The duration of this reversal is variable. It may be about a week, as in the Tazima earthquake of 1925 and the Tango earthquake of 1927; about 3 weeks, as in the Kwanto earthquake of 1923; about $2\frac{1}{2}$ months, as in the Marsica earthquake of 1915; about 1 year or a little more, as in the Messina earthquake of 1908 and the Mino-Owari earthquake of 1891, or about 2 years, as in the Hokkaido earthquake of 1894.

3. The effect of intensity on the daily maximum is illustrated in only one earthquake, the Kwanto earthquake of 1923, September 1. Dividing the after-shocks of the first month into two classes, according as the shocks were perceptible or imperceptible at Tokyo, the following epochs are obtained: September 2–10, 11 P.M. and 3 P.M.; September 11–20, $11\frac{1}{2}$ P.M. and 12 NOON; September 21–30, 12 NOON and 12 MIDT., showing that their epochs in all three intervals were practically opposed.

4. In the Tango earthquake of 1927, the mean focal depth is subject to a slightly marked diurnal period, the depth being greatest at 3 A.M., the same hour as the epoch of maximum frequency of the same earthquakes.

VOLCANIC EARTHQUAKES

The earthquakes that accompany and follow a volcanic eruption often occur in clusters so concentrated and of such brief duration that analysis becomes impossible. The present section is confined to Hawaiian earthquakes of the years 1922–24, and to the earthquakes attending the eruptions of two Japanese volcanoes, namely, those

[29] "Report on the Hawke's Bay Earthquake," *N.Z. Dep. Sci. Indus. Res. Bull., No. 43* (1933), pp. 105–6.

of the Asama-yama in 1911 (July 1–October 20) and the Komagatake in 1929 (June 24–July 10).[30]

TABLE XXIII

Volcano	No. of Shocks	Epoch	Amplitude
Hawaii	948	11½ A.M.	.14
Asama-yama	942	12 NOON	.35
Komagatake	364	12 NOON	.11

CONCLUSIONS

1. Excluding after-shocks, the maximum epoch of the diurnal period is determined in 64 records. In 24 of these, it falls at or near midnight, in 35 at or near noon, and in 5 others at from 4 to 5½ P.M. The average maxima for the first two groups are 0.25 A.M. and 0.40 P.M.

2. Of the 59 records in which the epoch falls near midnight or noon, the annual period is known in 37. When the epoch of the diurnal period falls near midnight, that of the annual period occurs in or near midwinter in 13 records and in or near midsummer in 5. When the epoch of the diurnal period falls near noon, that of the annual period occurs in or near midsummer in 16 records or in and near midwinter in 2. In one record (Table VII), the epoch of the diurnal period falls at about 5½ P.M. and that of the annual period at the end of May. Thus, in about 80 per cent of the records, the epochs of the diurnal and annual periods fall at noon and in summer, or at midnight and in winter. Of the other 7 exceptions, in one (Italy, 1891–1930) the diurnal epoch falls at 2 A.M. and the annual epoch in June; the others occur in records obtained at seismological observatories.

3. The opposed epochs of the diurnal period and the general relations between the diurnal and annual periods in regional earthquakes are probably connected with the directions of the crust displacements that cause the earthquakes. Let us suppose that an ex-

[30] *Hawaiian Volc. Obs. Month. Bull., 1922–24;* Omori, *Imp. Earthq. Inv. Com. Bull.*, Vol. VI (1914), pp. 115–226; F. Kishinouye, *Earthq. Res. Inst. Bull.*, Vol. VIII (1930), pp. 283–89.

ternal force acts downward on the earth, such, for instance, as atmospheric pressure, with a diurnal maximum about midnight and an annual maximum in midwinter. Then, if the earthquakes were mainly due to a depression of the crust, the diurnal and annual seismic epochs would occur about midnight and midwinter. On the other hand, if the earthquakes were mainly due to an elevation of the crust, the epochs would occur about noon and midsummer. It is worthy of notice that the midnight and winter maxima prevail in regions in which earthquakes are slight or of moderate intensity, and the noon and summer maxima in those visited by the most destructive shocks.

4. Assuming that a great earthquake is usually caused by an uplift of the crust, the displaced mass would at once begin to settle downward, and, during an interval that may last from a week to a year or more, the stronger after-shocks are caused by such downward slips. At the close of this interval, the forces that gave rise to the earthquake once more prevail, and further after-shocks, if they deserve that title, are due to the continued movements of elevation. It is interesting, however, to observe that, from the earliest days, after-shocks registered at any station may be caused by movements in both directions. For about 20 days after the Kwanto earthquake of 1923, the stronger after-shocks were due to subsidence, but they were accompanied by rather more numerous slighter shocks due to elevation. During the next 10 days, the stronger and more frequent after-shocks were due to elevation and the weaker shocks to subsidence.

PRELIMINARY SUBDIVISION OF THE KNOX DOLOMITE IN EAST TENNESSEE[1]

CHARLES R. L. ODER
Tennessee Division of Geology

ABSTRACT

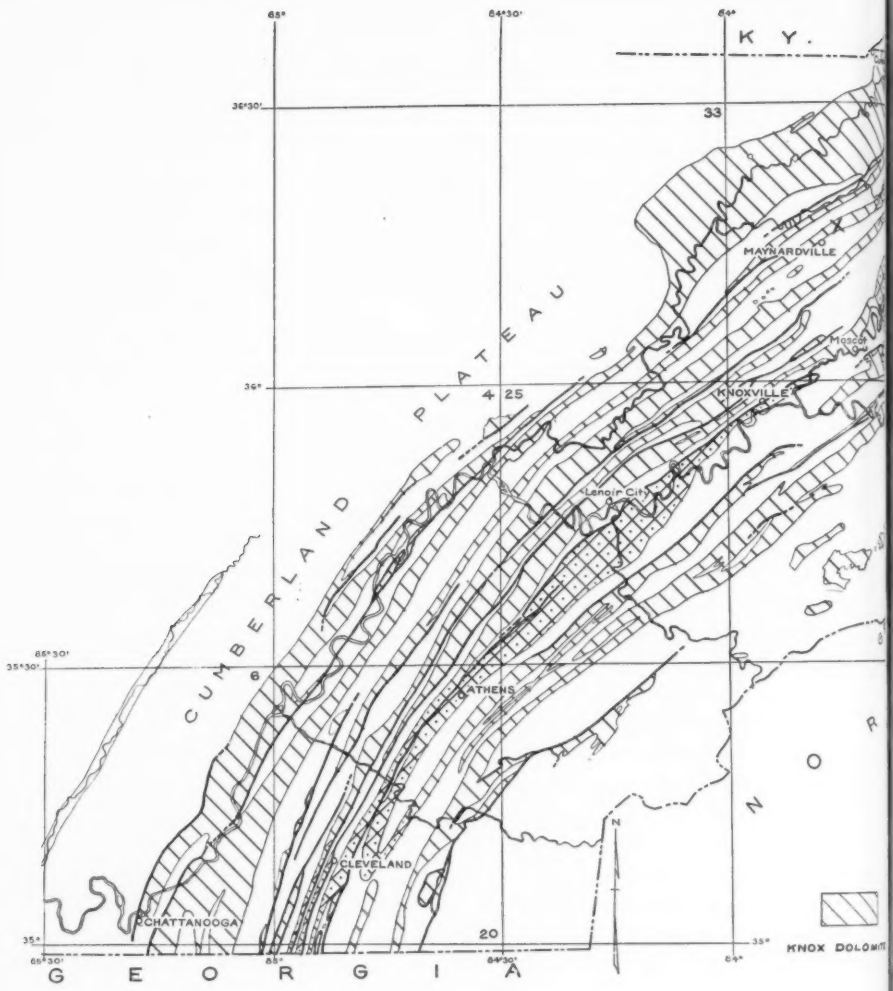
The Knox dolomite is subdivided in this article into seven formations, the lower three of which are referred to the top of the Cambrian, and the upper four to the basal series of the Ordovician system. The physical and faunal characteristics, stratigraphic relations, age, and correlation of the different units are discussed. The growth in knowledge of Knox stratigraphy is briefly summarized. A map shows the distribution of the Knox dolomite in the area and the belts that have been mapped in detail. A table gives the stratigraphic position, age, equivalents, and a brief history of the classification of the various Knox and closely related formations. Two measured sections, showing the eastern and western characters of the Knox dolomite, are given in some detail.

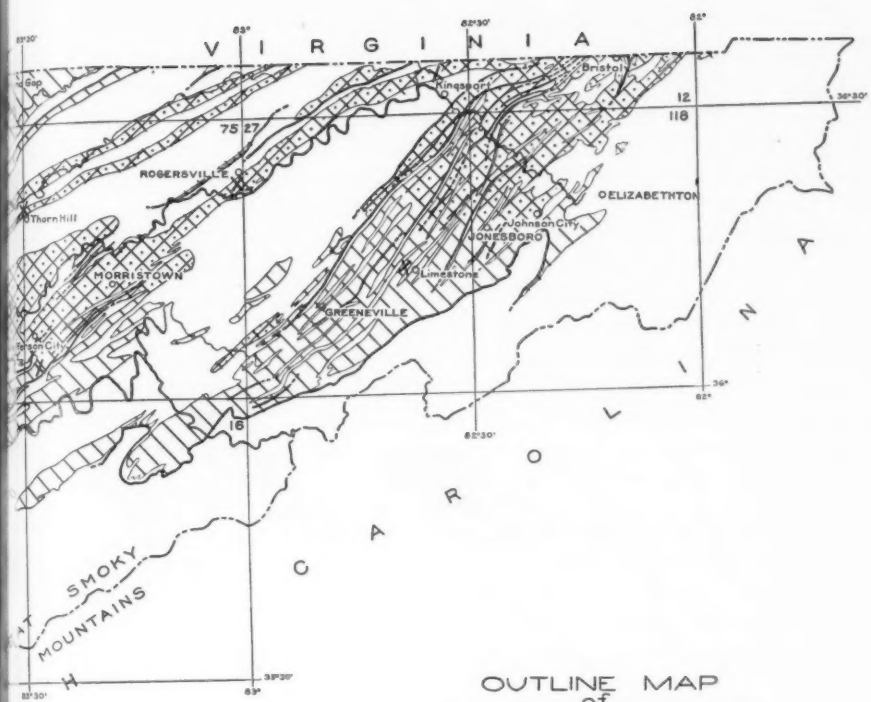
INTRODUCTION

The authors of the United States Geological Survey folios treating east Tennessee state that the Knox dolomite is the most important and most widespread of all the valley rocks. They were impressed by its extensive outcrop and its geological significance. Economic considerations further emphasize its importance, as it contains valuable zinc, lead, and barium deposits, marble, and other mineral products, much of the exploitation of which has been unprofitable, due, largely, to the lack of a proper understanding of the containing rocks. The need of adequate geologic maps and descriptions led the Tennessee Division of Geology, in 1929, to begin the mapping and subdivision of the Knox dolomite. This work was started by Dr. Josiah Bridge. The writer took up the investigation in 1930 and continued it through 1933. The area thus far investigated lies within that part of the Appalachian Valley known as the Great Valley[2] of east Tennessee. Field studies have covered approximately 2,000 square miles in seventeen counties.

[1] Published by permission of the Tennessee Division of Geology and the Graduate School of the University of Illinois. Most of the material set forth here was embodied in a thesis submitted to the Graduate School of the University of Illinois, June, 1933, in partial fulfilment of the requirements for the degree of Doctor of Philosophy. It has been modified by information subsequently obtained.

[2] The Valley, as it is generally called, extends from the Great Smoky Mountains on the east to the Cumberland Plateau on the west.


K Y.
MAYNARDVILLE
Maryville
KNOXVILLE
Lenoir City
CUMBERLAND PLATEAU
ATHENS
CLEVELAND
CHATTANOOGA
N O R
G E O R G I A
KNOX DOLOMITE
33
25
20
6
4
N



OUTLINE MAP of EAST TENNESSEE SHOWING DISTRIBUTION of KNOX DOLOMITE AND AREAS MAPPED IN DETAIL

BY

CHARLES R.L. ODER

SCALE

10 0 10 20 30 MILES

KNOX BELTS MAPPED IN DETAIL

FAULT

CONTACT

EXPOSED SECTION

Pl. I

GROWTH IN KNOWLEDGE OF KNOX STATIGRAPHY

Safford[3] introduced his "Knox or Knoxville Group" in 1869, naming it from Knoxville and Knox County, Tennessee. He subdivided the group, from the bottom upward, into "2c′, Knox sandstone," "2c″, Knox shale" and "2c‴, Knox dolomite." The latter is being dealt with here.

In 1891, Hayes[4] substituted "Rome sandstone and Weisner quartzite" for "Knox sandstone," "Conasauga shale" for "Knox shale," and "Chickamauga limestone and Rockmart slate" for "Trenton, Chazy or Maclurea," Safford's term for Ordovician beds overlying the Knox. "Knox dolomite" was retained for the top part of Safford's group. Hayes's terms were employed by the United States Geological Survey in the east Tennessee folios,[5] published between 1891 and 1907. Campbell,[6] however, split the Conasauga shale, beginning at the base, into the "Rutledge limestone," "Rogersville shale," "Maryville limestone," and "Nolichucky shale."

Ulrich[7] started the subdivision of the Knox dolomite. He has changed some of his earlier determinations and made further divisions and correlations. The present classification is due mainly to his work.

Purdue,[8] in 1912, and Secrist,[9] in 1924, described the zinc deposits of the Valley. They compiled stratigraphic discussions from the fo-

[3] J. M. Safford, *Geology of Tennessee* (1869), pp. 151 and 203–26.

[4] C. W. Hayes, "Overthrust Faults of the Southern Appalachians," *Geol. Soc. Amer., Bull. 2* (1891), pp. 141–52.

[5] *U.S. Geol. Surv. Geol. Atlas of the U.S.*, folios bearing directly on the region treated in this paper are: "Estillville, Va.-Ky.-Tenn.," *No. 12* (1894); "Knoxville, Tenn.-N.C.," *No. 16* (1895); "Cleveland, Tenn.," *No. 20* (1895); "Loudon, Tenn.," *No. 25* (1896); "Morristown, Tenn.," *No. 27* (1896); "Bristol, Va.-Tenn.," *No. 59* (1897); "Maynardville, Tenn.," *No. 75* (1901); "Greeneville, Tenn.-N.C.," *No 118* (1905); "Roan Mountain, Tenn.-N.C.," *No. 151* (1907).

[6] "Estillville, Va.-Ky.-Tenn.," *U.S. Geol. Surv. Geol. Atlas of the U.S., Folio No. 12* (1894).

[7] E. O. Ulrich, "Revision of the Paleozoic Systems," *Geol. Soc. Amer. Bull.* XXII (1911), pp. 635–41.

[8] A. H. Purdue, "Zinc Deposits of Northeastern Tennessee," *Tenn. State Geol. Surv., Bull. 14* (1912).

[9] M. H. Secrist, "Zinc Deposits of East Tennessee," *Tenn. Geol. Surv., Bull.* XXXI (1924).

lios; and Secrist gave a correlation table, constructed by Nelson from data supplied by Ulrich.

On the latest geologic map of Alabama, Butts[10] indicated some of the Knox formations, which he described, with figures of characteristic fossils, in the accompanying text. He also revised the Paleozoic map of Virginia,[11] on which related units are shown, and which are treated in a descriptive bulletin.

Bridge produced a detailed map, as yet unpublished, of the Knox beds from southwest of Mascot to Jefferson City, Tennessee. He has also described some of the related Missouri formations,[12] discussed their equivalents, and, in collaboration with Ulrich and Foerste, described and figured some of the fossils characteristic of the Upper Cambrian formations in that state. Dake and Bridge[13] recently discussed the equivalents of the Ellenburger limestone of Texas.

DESCRIPTION OF FORMATIONS

Table I shows that the Knox dolomite begins immediately above the Croixan series of the Cambrian and extends upward to the base of the Chazyan series of the Ordovician, its lower three formations comprising the Ozarkian series of the first system, and its upper four divisions forming the Canadian (Beekmantown) series of the second. As to the existence of unconformities at the boundaries of each rock series, the field evidence in Tennessee is neither clear nor uniform. Investigation has revealed no angular unconformities either at the base, summit, or within the Knox dolomite. The upper and lower boundaries in many places appear to be transitional, but in some localities they show conditions apparently indicative of local unconformity.

The object of this study is to describe those divisions of the Cambrian and Ordovician systems represented in the Knox dolomite.

[10] C. Butts, "Geology of Alabama, The Paleozoic Rocks," *Geol. Surv. Ala., Spec. Rept., No. 14* (1926), pp. 78–99, Pls. 9–20, with map.

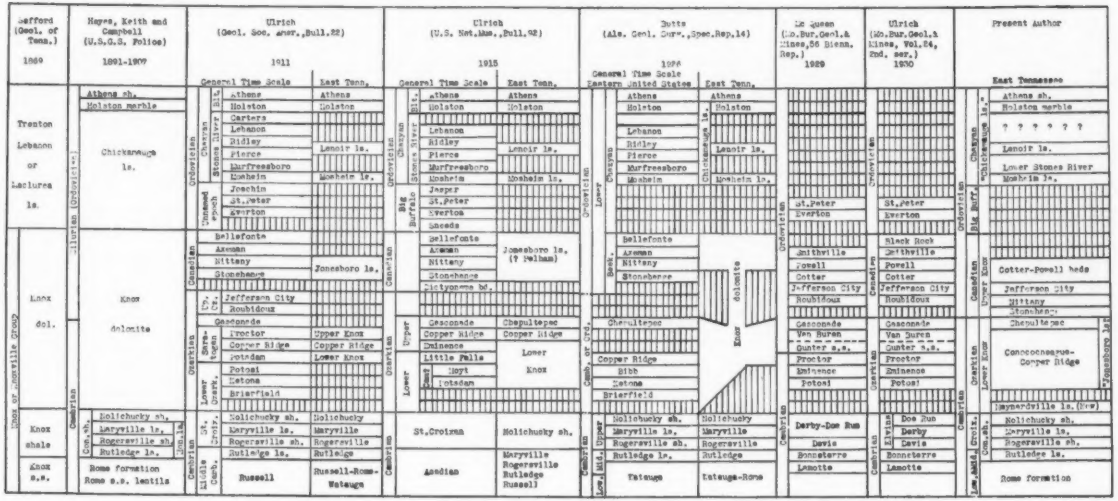
[11] "Geologic Map of the Appalachian Valley of Virginia with Explanatory Text," *Va. Geol. Surv., Bull.* XLII (1933), pp. 8–12, with map.

[12] Josiah Bridge, "Geology of the Eminence and Cardareva Quadrangles," *Mo. Bur. Geol. & Mines*, Vol. XXIV, 2d ser. (1930).

[13] C. L. Dake and Josiah Bridge, "Faunal Correlation of the Ellenburger Limestone of Texas," *Geol. Soc. Amer., Bull.* XLIII (1932), pp. 725–48.

TABLE I

SHOWING THE GROWTH OF THE CLASSIFICATION OF UPPER CAMBRIAN AND LOWER ORDOVICIAN FORMATIONS IN PORTIONS OF THE APPALACHIAN AND OZARK REGIONS OF THE UNITED STATES



The underlying and overlying formations are well treated in the older literature. As Table I gives the stratigraphic position, age, equivalents, and a brief history of the classification of the various units pertinent to this discussion, only descriptions of Knox formations will be given below.

THE CAMBRIAN SYSTEM

Ozarkian Series

MAYNARDVILLE LIMESTONE (NEW)

Name and stratigraphic relations.—This formation is named from Maynardville, the seat of Union County, Tennessee. It is well exposed along State Highway No. 33, about $5\frac{1}{2}$ miles northeast of the town, lying between the Nolichucky shale and the Conococheague-Copper Ridge formation.

Lithologic nature.—The Maynardville consists of 60–250 feet of thin-bedded to massive, light-bluish to dark-gray, fine- to coarse-grained, more or less laminated limestone, with dark-gray dolomite forming the upper third of the formation. The basal third carries limestone conglomerate in which small, black clay balls suggest oölitic textures. Sometimes thin, bluish-green calcareous shale occurs in the lower part. Dark-gray chert, with a medium-sized *Cryptozoon*, occurs sparingly in the upper beds. On the west side of the Valley the top is usually marked by 2 feet of dark-gray, shaly dolomite, with an undulating upper contact. The upper limit on the east side of the Valley is formed by 5–10 feet of sandstone. Thin arenaceous zones are present within the Maynardville. Aside from localities mentioned elsewhere in this paper, good exposures are found at the old "Lead Mine Bend" mine on Powell River, in Union County; along the Kingsport-Gate City Highway, 2 miles north of Kingsport; and along Gass Creek, 1 mile northeast of Greeneville.

Age.—This formation was, in places, formerly mapped with the Nolichucky shale. It was included, however, in the Knox dolomite on older geologic maps of Claiborne and Union counties. Its known fossils consist of problematical cystid plates and an unidentified species of *Cryptozoon*. Croixan trilobites occur in the Nolichucky up to the base of the Maynardville, but they have not been discovered within the latter. In lithology the Maynardville compares

with the lower Knox beds. Hence, it seems well to consider it, at least tentatively, as the basal member of the Knox dolomite, and as marking the beginning of Ozarkian deposition in east Tennessee.

CONOCOCHEAGUE-COPPER RIDGE FORMATION

Preliminary statement.—Lithologic diversity and fossil rarity make it difficult to recognize well-defined stratigraphic units in this zone which consists predominantly of dolomite on the west and of limestone on the east side of the Valley. Ulrich[14] applied the name "Copper Ridge chert" (later "Copper Ridge dolomite") to the western and "Jonesboro limestone" to the eastern representative. Due to its comprehensive nature, the latter term has been discarded. Butts[15] recently used "Conococheague limestone" for the eastern outcrops in Virginia. As to the age relations of these eastern and western occurrences, Ulrich and Butts differ. Ulrich considers the Conococheague older than the Copper Ridge; Butts contends that the two are facies of one formation. The writer, with reference to east Tennessee, believes that they are contemporaneous in age, and that their lithologic diversity is mainly attributable to varying degrees of dolomitization of the beds in different parts of the region.

Stratigraphic relations.—The base of the Conococheague-Copper Ridge rests upon the Maynardville limestone. Butts states that the "Copper Ridge" in Alabama is underlain by 2,600 feet of dolomite, the Brierfield, Ketona, and Bibb dolomites, which are said to be absent in Tennessee, indicating a significant hiatus between the Maynardville and Conococheague-Copper Ridge formations here. The Chepultepec normally overlies the Conococheague-Copper Ridge, but its universal occurrence in east Tennessee is doubtful. Observations have suggested the presence of several formations between the Maynardville and the Chepultepec, but sufficient evidence for establishing them is not in hand. Therefore, it seems advisable at present to treat this division as a composite formation, and to describe the mapable zones as members of it.

Morristown dolomite member.—The type locality of this unit is located along U.S. Highway No. 25-E, about 2 miles northwest of

[14] *Op. cit.*, pp. 635, 672.

[15] "Geologic Map of the Appalachian Valley of Virginia with Explanatory Text," *op. cit.*, p. 8.

Morristown, Tennessee. The Morristown extends from the top of the Maynardville limestone up to a thick arenaceous zone in the base of the next overlying member. It consists of 800–1,250 feet of thin to heavy-bedded, dark- to light-gray, dense to fine and medium crystalline, fine to coarsely laminated dolomite and limestone, with subordinate arenaceous and shaly zones. Very little limestone is present in the western outcrops, where the characteristic rock is a blackish- to brownish-gray dolomite, with a saccharoidal texture and a fetid odor. In the eastern areas, where the texture is dense in many places, limestone is always present in considerable quantities; in some localities it far exceeds, in others equals, but in spots is subordinate to, dolomite in volume. The proportion of limestone to dolomite varies radically in the north-central part of the Valley. Between Jefferson City and Morristown, this member is composed almost wholly of the western type of dolomite. In the vicinity of Morristown a few layers of limestone appear. Northeastward, along the strike of the same fold, the proportion of limestone gradually increases until it constitutes more than half of the member in the Bloomingdale region of Sullivan County. A striking black and white, coarse-grained, oölitic dolomite, often silicified, occurs in the lower part of the Morristown. Intraformational limestone conglomerates, somewhat silicified, appear at various levels. Five thin, arenaceous zones occur in the upper 200 feet. A pronounced difference between the eastern and western facies is the greater amount of sandstone in the lower 50 feet of the eastern outcrops, where the base contains 5–8 feet of it; and, from 30 to 50 feet above this a 2-foot sandy zone is present. Chert is usually most plentiful in the upper half, especially along the western outcrops. It varies from grayish-white and steel-gray to grayish-black, the darker colors being more abundant in the eastern areas. Dense, compact, conglomeratic, and oölitic textures are all common. Dark-gray, fine-textured, oölitic varieties characterize the lower, though white, oölitic cherts are most abundant in the upper part. Most of the Morristown chert has a jagged and pitted surface, and much of it contains the ancient seaweed *Cryptozoon*.

The important zinc and lead ores in the western half of the valley occur in fractured and brecciated zones, either along faults and joints or between such structures, in the lower third of this member and in

places extending downward into the top of the Maynardville limestone.

Almost complete exposures of the western facies are found along U.S. Highway No. 25-E, 2 miles northwest of Thorn Hill, Grainger County, and along State Highway No. 33, 5 miles northeast of Maynardville. Some of the best eastern exposures occur in the Jockey Creek section, described below, and 2 miles northwest of Bloomingdale, Sullivan County.

Fossils are rare in the Morristown. Several species of *Cryptozoa* have been recognized, including *C. proliferum* Hall and *C. aff. C. undulatum* Bassler. Small, triangular, silicified sections of chitons are occasionally seen in the upper limestones. The writer collected the trilobite *Stenochilina spinifera* Ulrich from near the top in Grainger County and *Calvinella minor* Ulrich and *C. cf. C. ozarkensis* Walcott from the same level in Greene County. Ulrich lists both of these forms as occurring in the *Calvinella zone* in the Eminence dolomite of Missouri. Faunal evidence, stratigraphic position, and generally similar lithology strongly support correlation of this member across the valley.

Bloomingdale limestone member.—The type section of this member is situated along a branch of Reedy Creek, 1½ miles northwest of Bloomingdale, 4 miles northeast of Kingsport, Tennessee. This unit lies between the top of the Morristown dolomite and a thin sandstone at the base of the Chepultepec formation. It embraces 170–650 feet of thin to heavy-bedded, light to dove and dark-gray, dense to medium crystalline, fine to coarsely laminated limestone and dolomite. Dolomite is minor in amount in the eastern, but makes up practically the whole of the western sections. The color and texture of this unit closely resemble those of the underlying member. Thin arenaceous zones occur at numerous levels, ten such sometimes being counted in a thickness of 100 feet. The base is formed by 3–15 feet of arenaceous and shaly dolomite and quartzitic sandstone. A 3-foot sandy zone usually appears 50–100 feet above the base, and the top is limited by 1–3 feet of sandstone. The Bloomingdale chert is scarcely distinguishable from that in the Morristown. Its quantity ranges from almost nil to abundance. Light- and dark-gray, fine to medium-textured, oölitic and conglomeratic varieties are common.

Cryptozoon proliferum Hall and *C. aff. C. undulatum* Bassler occur in compact cherts of both the upper and lower zones. This member is well displayed at most of the places mentioned for the Maynardville limestone and the Morristown dolomite.

Age and correlation.—The Conococheague-Copper Ridge formation belongs in the lower part of the Ozarkian series of the Cambrian system. The Copper Ridge facies has been traced southwestward into Alabama and northeastward through much of Virginia, and the Conococheague from Pennsylvania through Virginia at least halfway across Tennessee. The fauna found by Butts[16] in the Copper Ridge of Alabama somewhat doubtfully correlates it with beds in Missouri, which range from the Potosi up to the base of the Gasconade. Other age affinities are with at least the lower part of the Oneota dolomite in Wisconsin, with a lower zone in the Ellenburger limestone of Texas, and with Division *A* of Billings' section at Phillipsburg, Quebec.

CHEPULTEPEC FORMATION

Name and stratigraphic relations.—Ulrich[17] originally applied this name, from the town of Chepultepec, Blount County, Alabama, to the "Upper Knox," later restricting it to its present usage. Through much of east Tennessee, this formation lies between the Conococheague-Copper Ridge beds and the Nittany dolomite. A Stonehenge limestone equivalent, however, intervenes between the Nittany and the Chepultepec in at least one locality.

Lithologic nature.—In the western sections the Chepultepec is made up of 500 feet of light- to dark-gray, fine-grained to medium crystalline dolomite, with considerable light-gray, finely granular and oölitic chert. In the eastern areas it consists of 500–700 feet of dark- and dove-gray, fine-grained, fine to coarsely laminated limestone, with minor amounts of dolomite. Coarse limestone conglomerate occurs between 30 and 100 feet below the top. The base is formed by 1–3 feet of mixed, medium-grained, calcareous sandstone, arenaceous dolomite, and dark-gray chert. Thin arenaceous zones occur at various levels in the formation. Chert is usually abundant,

[16] "Geology of Alabama, the Paleozoic Rocks," *op. cit.*, pp. 86, 87; Pl. 14; Figs. 1–24; "Bessemer-Vandiver, Alabama," *U.S. Geol. Surv. Folio 221* (1927), p. 4.

[17] *Op. cit.*, p. 638.

varying from light-gray to yellow and black, and sometimes containing the *Cryptozoon* structure. Oölitic varieties occur in the basal zone. The characteristic types consist of a grayish-white, porous and mealy rock, which often resembles worm-eaten wood, and variegated, dark-colored, translucent chalcedony, with a dull to greasy luster. Much of the chert is fossiliferous, and some of it shows impressions of dolomite rhombs on its exterior. The brownish-red Chepultepec soil is strewn in many places with small, siliceous geodes and solid cavity fillings, similar in appearance to like masses from the Cotter beds. The Cotter types, however, are more cavernous and fragile and branch to a greater extent than do those of the Chepultepec. The majority of the latter are either solid balls, with a rough surface, or rosette discs.

The Chepultepec strata show some brecciated zones, in one of which, in Greene County, is a rich sulphide deposit probably genetically similar to higher ore zones to be discussed on pages following.

Good exposures of this formation occur ¾ of a mile north of Mount Horeb, Jefferson County; along State Highway No. 66, 2 miles southwest of Rogersville; and along State Highway No. 33, 5 miles northeast of Maynardville.

Organic remains.—The Chepultepec yields a fair number of fossils as casts in chert, cross and longitudinal sections in limestone and silicified specimens in the soil. They include *Cryptozoa*, a *Tetradium-like* coral, brachiopods, gastropods, cephalopods, and trilobites. *Cryptozoon aff. C. steeli*, *Syntrophina campbelli*, and *Hystricurus* have been taken along the upper boundary in chert that appears to have come from both the Nittany and the Chepultepec. *Helicotoma uniangulata*, which has been found in a few Tennessee localities, has been declared diagnostic of the Chepultepec and its equivalents. The following faunal zones have been outlined in the north central part of the valley.

1. *The Sinuopea gastropod zone*, occupying about the basal third of the formation, with *Sinuopea cf. S. obesa* Whitfield, *S. humerosa* Ulrich, *S.* 3 other sp., *Helicotoma uniangulata* (Hall), *Taeniospira* several sp., *Pondia powelli* Oder, and a *Tetradium-like* coral.

2. *The cyrtoceracone cephalopod and Gasconadia gastropod zone* occurs in about the mid-portions of the unit, with *Dakeoceras aff. D.*

normale Ulrich & Foerste, *D. aff. D. subcurvatum* Ulrich & Foerste, *D.* sp., *Burenoceras pumilum* Ulrich & Foerste, *B.* sp., *Levisoceras* 2 sp., *Clarkoceras* sp., *Gasconadia cf. G. putilla* (Sardeson), *G.* 2 other sp., *Hypseloconus* sp., *Euconia* sp., *Helicotoma uniangulata* (Hall), *Rhachopea aff. R. transitans* Ulrich & Bridge, *Taeniospira* sp., *Sinuopea vera* Ulrich & Bridge, *Sinuopea humerosa?* Ulrich, *S.* sp., *Ophileta aff. O. levata* Vanuxem, and *O. aff. O. profunda* Billings.

3. *The Ophileta zone* extends from 100 down to 250 feet below the top, with *Ophileta supraplana* Ulrich & Bridge, *O. aff. O. levata* Vanuxem, *O. aff. O. profunda* Billings, *O. cf. O. subalata* Ulrich, *O. cf. O. nerine* Billings, *Helicotoma cf. H. uniangulata* (Hall), *Eotomaria?* sp., *Ozarkina aff. O. complanata* Ulrich & Bridge, *O. aff. O. typica* Ulrich & Bridge, *Scenella* sp., *Cryptozoon aff. C. steeli* Seely (presence?), *Lingula* sp., *Syntrophina campbelli* (Walcott) (presence?), *Gasconadia* sp., *Levisoceras* sp., *Hystricurus cordai* (Billings), *H. missouriensis* Ulrich, and *H.* sp. (presence of last three?).

4. *The zone of the Endoceratidae* comprises the uppermost 150 feet of beds, with *Ophileta grandis* Ulrich, *Helicotoma cf. H. uniangulata* (Hall), *Cameroceras* 4 sp., *Endoceras* 3 sp., and *Colpoceras* 2 sp.

Age and correlation.—This unit forms the top of the Ozarkian series of the Cambrian system. It correlates with the Chepultepec of Alabama and Virginia and the Gasconade formation of Missouri. Portions of its fauna have been observed locally in the Appalachian Valley as far north as New York. Other correlatives are in the Oneota dolomite of Wisconsin, the Ellenburger limestone of Texas, the Mons of Alberta, and the Cass Fiord formation in Northern Greenland.

THE ORDOVICIAN SYSTEM

CANADIAN (BEEKMANTOWN) SERIES

STONEHENGE LIMESTONE

Stose[18] chose this term from Stonehenge, Guilford County, Pennsylvania. This unit intervenes between the Chepultepec formation and the Nittany dolomite in the northeastern part of the valley, not being known elsewhere in the area. It consists of 100–350 feet of medium- to heavy-bedded, dove to dark bluish-gray, fine-grained,

[18] "Mercersburg-Chambersburg, Pa.," *U.S. Geol. Surv. Geol. Atlas of U.S., Folio 170* (1909), p. 6.

partially crystalline, sparsely laminated limestone, with but little dolomite. The chert content is small. An excellent exposure occurs near Holston Valley, Sullivan County, about 6 miles southeast of Bristol. Here, *Eccyliopteris* and other fossils, said by Ulrich to fix its age, are present in the limestone. Butts[19] says: "The Stonehenge age of this limestone in the northern part of Virginia is shown by such fossils as *Ophileta complanata* and possibly *O. hunterensis*, both of which occur in the Tribes Hill limestone of New York, with which the Stonehenge is correlated."

NITTANY DOLOMITE

Name and stratigraphic relations.—Ulrich[20] applied this name from Nittany Valley, central Pennsylvania. This formation normally underlies the Jefferson City. It is underlain by the Stonehenge in some of the northeastern areas, and possibly in others. The Chepultepec appears to underlie it in the north-central and in most of the western valley areas, where its lower contact is apparently disconformable, due to the absence of the Stonehenge.

Lithologic nature.—The Nittany is composed of 25–250 feet of medium-bedded to massive, light-steel to dark-gray, finely crystalline, cherty dolomite, with thin arenaceous beds. In places, coarsely crystalline dolomite, similar to that in the Jefferson City, is present. White and dark-gray chert, in 1- to 5-foot beds, appears at intervals throughout its thickness, but most abundantly in the upper part. The prevalent type is a china-white to light-gray, brittle rock, mostly in angular blocks, some of which measure 5 feet square. Some of it is porous, with dolocastic textures. A white, oölitic variety ranges from 50 to 100 feet below the top. Mixture with and similarity of the chert to that in the lower Jefferson City obscures the boundary between these formations. The rare exposures of this contact usually show 1–2 feet of sandstone forming the upper limit of the Nittany, with the dove limestone of the Jefferson City beginning from 20 to 40 feet above. The topography to which the Nittany gives rise is often helpful to the stratigrapher. Many of the low valley ridges seem to be due to the resistant nature of its chert.

[19] "Geologic Map of the Appalachian Valley of Virginia with Explanatory Text," *op. cit.*, p. 11.

[20] *Op. cit.*, p. 658.

This unit, though rarely exposed, is represented in all of the Knox belts examined with the exception of the northeastern areas where it, as well as the Upper Canadian beds, is sometimes missing. The only complete exposures occur at the sites of the measured sections, given on following pages, and along State Highway No. 33, about $4\frac{1}{2}$ miles northeast of Maynardville.

Organic remains.—Every fossil found in the Nittany has been in chert. The forms collected by the writer include: *Cryptozoon aff. C. steeli* Seely, *C. cf. C. saxiroseum* Seely, *Sinuopea* sp., *Eotomaria?* sp., *Ophileta aff. O. levata* Vanuxem, *Lecanospira compacta* (Salter), *L. conferta* Ulrich, *L. salteri* Ulrich & Bridge, *Eccliopteris disjunctus* (Billings), *Eccyliomphalus calciferous* Whitfield, *Roubidouxia depressa* Butts, *Hormotoma aff. H. artemesia* (Billings), *Straparollus* sp., *Syntrophina campbelli* (Walcott), small orthoceraconic siphuncles, *Hystricurus missouriensis* Ulrich, and *H.* 3 other sp. Of the foregoing, the species of *Lecanospira* are the more common and quite diagnostic.

Age and correlation.—The presence of *Lecanospira* long has been taken to indicate the Lower Canadian age of the Nittany and its equivalents. It has been found at this horizon from Alabama to Eastern Canada, occurring in the Longview limestone of Alabama, the Nittany dolomite of Tennessee, Virginia, Maryland, and Pennsylvania, the lower part of Division *C* of the New York Beekmantown, and in beds of similar age in Northern Scotland and in Scandinavia. The Nittany fauna is closely akin to that of the Roubidoux formation of Missouri; it is represented in the middle part of the Arbuckle limestone of Oklahoma, and in the Ellenburger limestone of Texas. It is likewise known in the Lower Ordovician rocks in the Rocky Mountain trough, although the species in the western and in the Oklahoma formations are said to differ from the eastern types.

JEFFERSON CITY FORMATION

Name.—Winslow[21] used this name for beds lying between the Roubidoux and the St. Peter sandstones at Jefferson City, Missouri. Ulrich[22] divided Winslow's formation into three, restricting the term

[21] A. Winslow, "Lead and Zinc Deposits of Missouri," *Mo. Geol. Surv.*, Vol. VI (1894), pp. 133–34.

[22] "Bassler's Bibliographic Index of American Ordovician and Silurian Fossils (in back)," *Bull. U.S. Nat. Mus.*, Vol. II, No. 92 (1915), Pl. 2.

"Jefferson City" to the lower and inserting two higher formations, the Cotter and Powell, between it and the upper sandstone. He failed to describe his new formations; but Purdue and Miser[23] soon employed his classification in northwest Arkansas, and Weller and St. Clair[24] applied his Jefferson City restriction in Ste. Genevieve County, Missouri. Ulrich, considering the Upper Knox formations to bear closer similarities to their Missouri than to their Appalachian equivalents, introduced the Missouri terms into Tennessee in 1929. These names are now used locally and have made their way into the geological literature of the region. Consequently, the writer has decided to employ them here.

Stratigraphic relations.—The Jefferson City occupies the interval between the top of the Nittany and the base of the Cotter-Powell beds. No strong field evidence of widespread unconformity at either its base or summit has been found. The presence of thin sandstones might suggest such, but all of the Knox formations are more or less arenaceous. Local gaps occur at the top of this unit. It is but 175 feet thick in some of the western localities, whereas in the eastern areas the thickness reaches 400 feet, and the upper part, in the east, carries a trilobite fauna that has not been found in the west.

Lithologic nature.—The Jefferson City is made up of 55–400 feet of thin- to heavy-bedded, dove- and dark- to brownish-gray, fine-grained limestone and extremely light- to dark-gray, fine-grained to dense dolomite. Thin, greenish-blue, siliceous shales occur along some of the bedding planes. Coarse "edgewise" limestone conglomerates are occasionally present. The volume of limestone varies from thin beds, in the western sections, to zones as much as 100 feet thick, in the lower half of the formation in some eastern localities. The base usually contains from 1 to 2 feet of light-gray, calcareous sandstone, which is ordinarily overlain by coarsely crystalline, light-gray dolomite. Thin arenaceous horizons occur toward the top. The principal sulphide ore horizons in the Knox dolomite in the eastern half of the valley occur in this formation. They range from 100 feet

[23] A. H. Purdue and H. D. Miser, "Eureka Springs-Harrison, Arkansas," *U.S. Geol. Surv. Atlas of U.S., Folio. 202* (1916).

[24] S. Weller and S. St. Clair, "Geology of Ste. Genevieve County, Missouri," *Mo. Bur. Geol. and Mines*, Vol. XXII, 2d ser. (1928), p. 75.

below the top to within 25 feet of the base, usually consisting of two or three richly mineralized zones, each varying from 10 to 75 feet in thickness. The sphalerite and galena (when present) occur in brecciated, recrystallized, and dolomitized rock. Recrystallization gives the strata of such zones a coarse texture. The unrecrystallized limestone often has a brownish hue, suggesting the term "brown lime" (of Newman). Commonly, portions of the "brown lime" have been both recrystallized and dolomitized. In some of the western localities the Jefferson City beds have a fine to medium, uniformly crystalline texture, and are streaked with shades of red, brown, purple, and green. Iron-bearing solutions have deposited ferric oxide along thin laminae, bedding planes, and minute fractures, producing a variety of beautiful designs. These characters, combined with the thick and well-bedded nature of the rocks, have made them valuable as marble. The Lower Jefferson City has thick beds of grayish-white, brittle, partially fossiliferous chert, which is usually mixed with similar material from the Upper Nittany, covering the boundary between the two formations. It is seldom, however, that more than 20 feet of the Lower Jefferson City are as cherty as the Nittany, and in most cases Nittany fossils appear about 25 feet below the lowest dove limestone of the former. Grayish-white, oölitic chert occurs in the lower part; the middle usually has a black, rough-surfaced variety which contains shells of *Oraspira bigranosa* Ulrich. Steel- and lighter gray types are common, in small quantities, at various levels. Thick layers of white, fossiliferous chert have been found in the upper 50 feet.

This formation is completely exposed in the measured sections, given on following pages. Other outcrops are found on the northern edge of Kingsport and along State Highway No. 33, 4½ miles northeast of Maynardville.

Organic remains.—Fossils are fairly numerous in the Jefferson City chert. Sections of gastropods are common in the limestone. The residual soil frequently holds silicified specimens of the operculum *Ceratopea*, orthoceraconic and piloceratoid siphuncles, and small gastropods. Three poorly defined faunal zones may be outlined as follows:

1. *The lower or Hormotoma zone*, extending from the base for ap-

proximately 50 feet upward, with *Hormotoma artemesia* (Billings), *H.* 2 other sp., *Oraspira cf. O. bigranosa* Ulrich, *O.* large sp., *Coelocaulus linearis* (Billings), *Roubidouxia cf. R. depressa* Butts, *Lecanospira* sp., *Ophileta* 3 sp., *Liospira* sp., *Ceratopea subconica* Oder, and *Schroederoceras-like* cephalopods.

2. *The middle or Oraspira zone,* extending roughly from 50 feet above the base to within 100 feet of the top, with *Oraspira bigranosa* Ulrich, *O.* 2 other sp., *Hormotoma aff. H. artemesia* (Billings), *Coelocaulus* sp., *Maclurites aff. M. affinis* (Billings), *Helicotoma* sp., *Platycolpus capax* (Billings), and *Schroederoceras-like* cephalopods.

3. *The upper or trilobite zone,* reaching from near the top downward for 100 feet, with *Oraspira* sp., *Maclurites aff. M. affinis* (Billings), *Hormotoma aff. H. gracilens* (Hall), *H. artemesia* (Billings), *Coelocaulus linearis* (Billings), *Ophileta* several small sp., *Ceratopea cuneata* Oder, *C. robusta* Oder, *C. capuliformis* Oder, *C. sulcata* Oder, *C. subconica* Oder, *C. calceoliformis* Oder, *C. tennesseensis* Oder, *Deltatreta elegantula* Butts, *Dalmanella? evadne* (Billings), *Cameroceras* sp., *Endoceras* sp., *Piloceras* sp., *Platycolpus capax* (Billings), *Bathyurus amplimarginatus* Billings, *B.* 2 other sp., and *Hystricurus* 2 sp.

Age and correlation.—The Jefferson City fauna places it in the Canadian series of the Ordovician system. It correlates, at least in part, with the Newala limestone of Alabama, the Axeman limestone of Pennsylvania, the upper part of Division *C* of the New York Beekmantown, and the Beekmantown equivalents of Virginia, Maryland, and Newfoundland. It is said to be the equivalent of the Jefferson City formation of Missouri and Arkansas, which correlates with the lower upper part of the Arbuckle limestone in Oklahoma, with at least part of the Shakopee formation in Iowa, Wisconsin, Minnesota, and Illinois, and with a portion of the Ellenburger limestone of Texas.

COTTER-POWELL BEDS

Name.—This designation represents two names, introduced by Ulrich[25] when he subdivided Winslow's Jefferson City formation. The first term was adopted from the town of Cotter, Baxter County, Arkansas, and the second from Powell station, Marion County,

[25] "Bassler's Bibliographic Index, etc.," *op. cit.*

Arkansas. The writer has never examined any definitely known Powell beds, which belong above the Cotter. The fossils from the horizon here described appear to be of Cotter age. Ulrich states that the upper strata of the Knox dolomite, in some Tennessee localities, represent the Powell formation of Missouri. In the absence of definite evidence, and since the name Cotter-Powell has been introduced, it seems best to use it until the presence or absence of a Powell equivalent in the area is proved.

Stratigraphic relations.—The Cotter-Powell beds, which form the top of the Knox dolomite, lie between the top of the Jefferson City and the base of the Chazyan. The basal contact does not appear to be one of pronounced unconformity. In the eastern half of the Valley the overlying formation is the Mosheim limestone. Frequently, it is missing and the Lenoir limestone rests upon the Cotter-Powell beds; in a few places the Athens shale is in contact with these sediments. On the west side of the Valley the Knox is overlain by lower Stones River limestones, similar to the Chazyan beds in the Central Basin of Tennessee. In some localities the upper strata are conglomeratic, seemingly indicating local erosion in this region at the end of Canadian time. But in many areas the upper boundary is transitional into the Chazyan limestone.

Lithologic nature.—This division is made up of 265–755 feet of thin- to heavy-bedded, light- and dark-gray, fine-grained, moderately laminated dolomite and limestone, with thin, sandy phases. The limestone content ranges from nothing in some of the western areas to nearly one-half of the unit in the east. Fine- to medium-textured limestone conglomerate is found near the middle. Some of the lightest-colored and finest-textured dolomite of the Knox occurs in these beds. In some of the western sections the strata are crystalline and variously colored, forming marble like that described under the Jefferson City. The base is marked by from 4 inches to 1 foot of light-gray, fine- to medium-grained sandstone, some of which is quartzitic. Several thin arenaceous zones appear, sporadically, from the base to above the middle. The uppermost 2 feet are sometimes conglomeratic, with angular to rounded, calcareous, cherty, and arenaceous pebbles disseminated through the dolomite. This condition occasionally extends upward into the base of the Mosheim lime-

stone. Keith[26] found that the upper 100 feet of the Knox is conglomeratic 2 miles northeast of Luttrell. The Jefferson City ore zones, described above, in places extend well up into the Cotter. Chert is never so abundant in the Cotter-Powell as in the underlying formations, although thick beds of it sometimes appear in the top of this unit in the western localities. The chert varies from china-white to dark-gray, and from compact to oölitic and conglomeratic. A characteristic, hard, dull steel-gray, oölitic variety occurs between 50 and 75 feet above the base. Reddish-brown clay soil marks the Cotter-Powell outcrop. Cherty débris seldom forms a dense covering of this soil, but numerous small, siliceous geodes, the types of which have been compared with those of the Chepultepec formation, particles of ropy chert, and silicified fossils are found in the soil along the outcrop of the lower half of these beds.

This unit is more generally exposed than any of the others in the Knox dolomite. Good exposures occur at the sites mentioned under the other formations, particularly the Nittany and Jefferson City.

Organic remains.—The fossils, listed below, from the lower 200 to 400 feet of this zone, apparently constitute a Cotter fauna. The common forms are silicified siphuncles and species of *Ceratopea*, although brachiopods, trilobites, and gastropods are frequently present. The list includes: *Deltatreta* sp., *Taffia* sp., *Oraspira* small sp., small *Ophiletas*, *Turritoma acrea* (Billings), *Coelocaulus linearis* (Billings), *Hormotoma aff. H. gracilens* (Hall), *H. aff. H. artemesia* (Billings), *H. cf. H. vesta* (Billings), *Holopea* sp., *Helicotomoa* sp., *Ceratopea keithi* Ulrich, *C. compressa* Oder, *C. corniformis* Oder, *C. tennesseensis* Oder, *C. calceoliformis* Oder, *C. robusta* Oder, *C. capuliformis* Oder, *C. cuneata* Oder, *Cameroceras brainerdi* (Whitfield), *C. cf. C. curvatum* Ruedemann, *C.* 2 other sp., *Endoceras champlainense* Ruedemann, *E.* 3 other sp., *Piloceras canadense* Billings, *P.* 3 other sp., *Orthoceras cf. O. adamsi* Butts, *Barrandeoceras?* sp., *Schroederoceras-like* cephalopods, *Platycolpus aff. P. barabuensis* (Whitfield), and *Pliomerops? cf. P. convexus* (Billings).

Age and correlation.—This Knox division belongs in the Upper Canadian series of the Ordovician system. It is said to correlate with

[26] A. Keith, "Maynardville, Tenn.," *U.S. Geol. Surv. Geol. Atlas of U.S., Folio No. 75* (1901), p. 2.

the Cotter and Powell formations of Missouri and Arkansas, the Upper Arbuckle limestone of Oklahoma, and, in part, with the higher beds in the Ellenburger limestone of Texas. It has affinities with the upper part of the Newala and the whole of the Odenville limestone in Alabama, and, in part, with the Bellefonte dolomite of Virginia and Pennsylvania.

GEOLOGIC SECTIONS

The marked similarity in rock character of the Knox formations makes it difficult to describe them in such a manner as to render them distinguishable. Their insoluble residues have proved to be of practical value, but they cannot be discussed here. Close comparison of the cherts reveals differences that are helpful in mapping, but only experience in handling the cherts will give them utility. Hence, it seems worth while to supplement the foregoing treatment with detailed, measured sections. Two completely exposed sequences, displaying the eastern and western characters, were found. Their description follows.

THORN HILL SECTION IN GRAINGER COUNTY

Along U.S. Highway No. 25-E, in Grainger County, almost a continuous rock cut, extending from the crest of Clinch Mountain northwest to Indian Creek, exposes formations ranging in age from Lower Cambrian to Lower Silurian. Its length is about $3\frac{1}{2}$ miles and its thickness approximately 9,000 feet. The average strike is N. 50° E. and the dip 35° SE. The portion in which the Knox dolomite is exposed has become a standard locality for the study of this group. It is commonly called the "Thorn Hill section," from its nearness to the village of Thorn Hill. Ulrich made this section the type of his "Copper Ridge."

ORDOVICIAN

CHAZYAN SERIES

Mosheim Limestone

Limestone—thin- to heavy-bedded; dove-colored; fine-grained to semi-crystalline ..... (lower 15 feet)

CANADIAN (BEEKMANTOWN) SERIES (1,020.5 FEET)

	FEET
Cotter-Powell Beds (590.5 feet)	
Dolomitic limestone—steel-gray; fine-grained; upper 3 feet grades into dove limestone like that in Chazyan beds	10.0

	FEET
Dolomite and limestone—massive to medium-bedded; steel- to dark-gray; fine-grained; mottled; faintly banded; small nodules of light, and dark-gray chert	37.0
Dolomite—thin- to heavy-bedded; light- to dark-gray; fine-grained; mottled; faintly banded; thin, greenish shale along bedding; a little light- and dark-gray chert; 6 feet of lead-gray limestone at base	63.0
Dolomite—thin-bedded to massive; light- to dark-gray; fine-grained; mottled; shale along bedding; few areas of sphalerite; a little light-gray chert; 2 feet of blue, banded dolomite at base	27.0
Dolomite and limestone—thin- to heavy-bedded; light- to dark-gray; fine-grained to crystalline; laminated; mottled; small chert areas; thin greenish shale 1 foot above base; thin gray chert in base	15.0
Dolomite—thin- to heavy-bedded; light- to dark-gray; dense to finely crystalline; slightly mottled; 1 foot of grayish-white and dark-gray chert at base	22.0
Dolomite—thin- to heavy-bedded; light- to dark-gray; fine-grained; finely laminated; thin layers of light- and dark-gray, arenaceous and oölitic chert	32.5
Dolomite—thin- to heavy-bedded; light to lead-gray; fine-grained; mottled; thin, light-gray, arenaceous and oölitic chert 15 feet below top; 3 inches of arenaceous dolomite 35 feet below chert	74.0
Dolomite—thin- to heavy-bedded; light steel- to dark lead-gray; fine-grained; thin, greenish shale along bedding; mottled; beds of light-gray chert, up to 18 inches thick; *Ceratopea robusta* in soil	41.0
Dolomite—heavy-bedded; light- to lead- and maple-gray; fine-grained; small siliceous geodes; two ½- to 6-inch layers of light-gray chert, with small *Oraspira* and *Hormotoma cf. H. gracilens*, near middle; lenses of light-gray, sparsely arenaceous chert in base; *Ceratopea subconica* in soil	24.5
Dolomite—thin- to heavy-bedded; light- to dark-gray; fine-grained; brecciated; small areas of sphalerite; upper 2 feet with arenaceous and oölitic chert; several thin layers of light-gray chert; thin arenaceous dolomite and chert a little below middle	71.5
Dolomite—medium- to heavy-bedded; steel-gray; crystalline to dense; 2 inches of light-gray chert at top; 2 inches of white chert near base; 2 feet of lead-gray limestone at base	28.0
Dolomite—thin- to heavy-bedded; light- to dark-gray; fine-grained; 2 inches of white chert near top; arenaceous dolomite and chert just below middle; dark-gray limestone forms basal 3 feet, with 1 inch of white chert at base	25.5
Dolomite—thin- to heavy-bedded; light- to dark-gray; fine-grained; brecciated; few areas of sphalerite; a little white chert; grayish-white, oölitic chert and arenaceous dolomite in two thin zones 7 and 9 feet above base	64.0

	FEET
Dolomite—medium- to heavy-bedded; light- to dark-gray; fine-grained; light- and dark-gray chert nodules; 1 foot of arenaceous dolomite 12 feet below top; 1 foot of blue steel-gray, arenaceous dolomite and quartzitic sandstone at base	55.5
Jefferson City Formation (248 feet)	
Dolomite—medium- to heavy-bedded; steel- to dark-gray; fine-grained to crystalline; mottled; brecciated; small areas of sphalerite; a little light-gray chert; arenaceous and oölitic chert 7 feet below top	33.0
Limestone—thin- to heavy-bedded; fine-grained to coarsely crystalline; dove- to dark-gray; small siliceous geodes; thin slabs of light-gray chert; 1 foot of mixed grayish-white chert and shale at top; three 2-inch layers of grayish-white chert, with *Oraspira bigranosa*, 14 feet below top	64.5
Dolomite and limestone—medium- to heavy-bedded; steel- to dark-gray; fine-grained to coarsely crystalline; brecciated; small areas of sphalerite; 2 inches of light-gray chert 10 feet below top; thin grayish-white chert, with *Ceratopea cuneata*, near base	36.0
Limestone and dolomite—thin- to heavy-bedded; dove-, steel-, and lead-gray; fine-grained to coarsely crystalline; 6 inches of grayish-white chert, with *Hormotoma*, at base	29.5
Limestone and dolomite—medium- to heavy-bedded; dove- to dark-gray; fine-grained to medium crystalline; 1 foot of obscurely oölitic limestone at top; arenaceous zone near middle; considerable blue-gray chert	10.0
Dolomite—heavy-bedded; steel-gray; fine-grained; 1- to 18-inch layers of light-gray chert; 2 feet of dove limestone, with nodules of light-gray chert, at top	21.0
Limestone and dolomite—heavy-bedded; dove- and steel-gray; fine-grained to crystalline; thin layers of light-gray chert near top; 6 inches of dark-gray chert and shaly limestone near middle; three 1-inch zones of grayish-white chert near base	15.0
Dolomite—heavy-bedded; light-gray; medium to coarsely crystalline; 4 feet of thin-bedded, dove limestone at top; 2 feet of light-gray, calcareous sandstone at base	39.0
Nittany Dolomite (182 feet)	
Dolomite—thin- to heavy-bedded; light-gray; crystalline; beds of grayish-white chert, to 2 feet thick, with *Lecanospira compacta;* 1 foot of mixed arenaceous dolomite and oölitic chert at base	32.0
Dolomite—heavy-bedded; steel-gray; dense to crystalline; beds of white chert, to 1 foot thick; 1 foot of calcareous sandstone and chert at base	22.0

FEET

Dolomite—medium- to heavy-bedded; light to dark steel-gray; laminated; brecciated; a few areas of sphalerite; thin, white, oölitic chert 6 feet below top; 4 inches of grayish-white, arenaceous chert near middle; a few thin layers of dark-gray and grayish-white chert in lower half 48.0

Dolomite—medium- to heavy-bedded; dark- to light-gray; medium crystalline; thin, arenaceous seams in upper half; arenaceous and oölitic chert near middle; white, oölitic chert 15 feet above base.. 50.0

Dolomite—thin- to medium-bedded; light- to lead-gray; medium crystalline; laminated; 1-inch layers of dark-gray chert; 1 foot of calcareous sandstone at base; *Hystricurus missouriensis*, *Syntrophina campbelli*, and *Sinuopea* in "float" chert 30.0

CAMBRIAN

OZARKIAN SERIES (1,790 FEET)

Chepultepec? Formation (291 feet)

Dolomite—thin- to heavy-bedded; light- to dark-gray and brownish; dense to medium crystalline; a few thin layers of light- and dark-gray chert; light-gray, oölitic chert 32 feet below top; white and dark-gray, arenaceous, oölitic, and conglomeratic chert at base 92.0

Dolomite—thin- to medium-bedded; dark- to steel-gray; fine-grained; a little light-gray and black chert; 6 inches of light-gray, calcareous sandstone at base 120.0

Dolomite—thin- to medium-bedded; light to dark-gray; fine-grained to medium crystalline; nodular, black chalcedony 12 feet below top; a few thin layers of light- and dark-gray chert; 2 feet of maple-gray, arenaceous dolomite and dark-gray chert at base.... 59.0

Dolomite—thin- to medium-bedded; light- to dark-gray and brownish; fine to medium crystalline; 3 feet of calcareous sandstone at base, with undulating lower contact 20.0

Conococheague-Copper Ridge Formation (1,379 feet)

Bloomingdale limestone member (181 feet)

Dolomite—thin-bedded; dark- to light-gray; fine-grained; 2½ feet of light- and dark-gray, arenaceous and shaly dolomite and sandstone at base 18.0

Dolomite—thin- to medium-bedded; light- to dark-gray; fine to medium crystalline; 5 feet of thin-bedded to shaly, arenaceous dolomite, chert, and quartzitic sandstone at base 30.0

Dolomite—thin- to heavy-bedded; mostly light-gray; fine-grained to crystalline; thin zones of light- and dark-gray chert; 6 inches of arenaceous chert at base 33.0

Dolomite—thin- to heavy-bedded; light- to dark-gray and brown-

	FEET
ish; a little dark-gray chert; 2 feet of grayish-white chert, with *Cryptozoon aff. C. undulatum*, at base	50.0
Dolomite—thin- to medium-bedded; light- to dark-gray; fine to medium crystalline; 10 feet of thin-bedded to shaly, arenaceous dolomite and quartzitic sandstone at base	50.0
Morristown dolomite member (1,198 feet)	
Dolomite—thin- to medium-bedded; light- to dark-gray and brownish; fine to coarsely crystalline; 4 inches of dark-gray chert at top; several beds of grayish-white chert with *Cryptozoon aff. C. undulatum;* 1 foot of calcareous sandstone 25 feet above base; *Stenochilina spinifera* in "float" chert	54.5
Dolomite—thin- to medium-bedded; light- to dark-gray; fine-grained; laminated; 1 foot of arenaceous dolomite at base	18.5
Dolomite—thin- to medium-bedded; dark brownish to light-gray; finely crystalline; 18 inches of white, oölitic chert beneath thin, sandy seams 10 feet below top; 18 inches of steel-gray chert 16 feet below top, with *Cryptozoon aff. C. undulatum*	31.5
Dolomite—thin- to heavy-bedded; light- to dark-gray; fine-grained; light- and dark-gray chert near top; 2 feet of calcareous sandstone at base	66.0
Dolomite—thin- to medium-bedded; dark- to light-gray; fine to medium crystalline; thin layers of dark-gray chert; 1 foot of calcareous sandstone 11 feet below top	49.0
Dolomite—thin- to medium-bedded; light- to dark-gray; fine-grained to crystalline; considerable light- and dark-gray chert near top, with *Sinuopea* and *Cryptozoon aff. C. undulatum;* 1 foot of white, oölitic chert 50 feet below top; 1 foot of calcareous sandstone at base	145.0
Dolomite—thin- to medium-bedded; steel- to dark-gray; finely crystalline; weathered surface with narrow solution grooves; thin layers of dark-gray chert	110.0
Dolomite—thin-bedded to massive; dark- to light-gray; finely crystalline; occasionally with *Cryptozoon proliferum;* a few steel-gray chert nodules; 1 foot of grayish-white, oölitic chert at top	96.0
Dolomite—thin- to heavy-bedded; light- to dark-gray; finely crystalline; finely laminated; nodular and drusy	300.0
Dolomite—thin-bedded; dark-gray; crystalline; 1 foot of dark-gray, brecciated, cherty limestone at top; *Cryptozoon proliferum* in steel-gray chert 25 feet below top	75.0
Dolomite—thin- to medium-bedded; dark-gray; crystalline; small areas of sphalerite; *Cryptozoon proliferum* in steel-gray chert near middle; 2½ feet of dark-gray limestone at base	56.0

	FEET
Dolomite—thin-bedded to massive; dark- to light-gray; drusy; mottled; three 6-inch beds near middle, with *Cryptozoon aff. C. undulatum;* thin, fine-textured, black and white, oölitic chert 20 feet above base	146.5
Dolomite—thin-bedded to massive; steel- to dark-gray; finely crystalline; 18 inches of coarse-grained, black and white, oölitic dolomite at top; 18 inches of dark-gray, calcareous shale at base	18.0
Dolomite—shaly to medium-bedded; dark-gray; fine to coarsely crystalline; mottled; thin, light-gray chert conglomerate near top; 5 feet of magnesian limestone and greenish shale at base	30.0
Dolomite—dark steel-gray; fine-grained; surface mottled white; lower half shaly, with undulating basal contact	2.0
Maynardville Limestone (New, 120 feet)	
Dolomitic limestone—thin- to medium-bedded; dark steel-gray; fine-grained; basal 6 inches dark blue-gray, pure limestone	36.0
Shale—greenish-gray; highly calcareous	11.0
Limestone—thin- to heavy-bedded; fine-grained; dark blue-gray; mottled by fine, yellow clay partings; highly laminated; magnesian toward top	73.0

CROIXAN SERIES

Nolichucky Shale

Upper 150 feet: fine-grained to crystalline limestone, interbedded with gray, greenish, drab, and yellow, calcareous to clay shales; *Crepicephalus* and other Croixan trilobites, sporadically, throughout this thickness.

JOCKEY CREEK SECTION IN GREENE COUNTY

This section was measured along Jockey Creek, $\frac{1}{5}$–1 mile northwest of the town of Limestone, which is situated in Washington County, though the exposure of the Knox dolomite is located in Greene County. The strata are vertical, the strike varying from N. 45° E. to N. 55° E.

ORDOVICIAN

CHAZYAN SERIES

Athens Shale	
Shale—black; fissile	50.0+
Unexposed	82.0
Lenoir Limestone	
Limestone—grayish-black; nodular	70.0
Unexposed	26.0

	FEET
Mosheim Limestone?	
Limestone and dolomite—interbedded; limestone dove-gray, semi-crystalline, of Mosheim type; dolomite light- to dark-gray, fine-grained, of upper Knox character	12.0
CANADIAN (BEEKMANTOWN) SERIES (494.5 FEET)	
Cotter-Powell Beds (412 feet)	
Dolomite and limestone—medium- to heavy-bedded; fine-grained; light- to dark-gray and brownish; finely laminated; 1 foot of arenaceous limestone at base	88.0
Limestone and dolomite—medium- to heavy-bedded; fine-grained; finely laminated; limestone dove- to dark-gray; dolomite steel-gray; 6 inches of arenaceous limestone 15 feet below top; 1 foot of black chert at base	34.0
Limestone and dolomite—thin- to heavy-bedded; fine-grained; dove- to dark-gray; laminated; 6 inches of arenaceous limestone at base	162.0
Limestone and dolomite—medium-bedded; fine-grained; dove-, steel-, dark-gray, and brownish; dark-gray chert near top; 1 foot of sparsely arenaceous limestone at base	17.5
Dolomite and limestone—thin- to medium-bedded; fine-grained; steel-, dark-gray, and brownish; 6 inches of arenaceous dolomite 3 feet below top and 1 foot of same at base	8.5
Dolomite and limestone—medium-bedded; fine-grained; dove-, steel-, and dark-gray; a little dark-gray chert; 18 inches of arenaceous dolomite 2½ feet below top; 1 foot of arenaceous limestone 18 inches above base	8.5
Dolomite and limestone—thin- to heavy-bedded; fine-grained; dove-, steel-, and dark-gray; laminated; thin arenaceous zones at intervals; a little light- and dark-gray chert toward base	51.0
Limestone and dolomite—medium- to heavy-bedded; fine-grained; dove-, steel-, and lead-gray; finely laminated; several thin sandy zones; 1 foot of calcareous sandstone at base, with slightly undulating lower contact	42.5
Jefferson City Formation (55 feet)	
Limestone and dolomite—medium- to heavy-bedded; fine-grained; dove-, steel-, and lead-gray; lower 2½ feet somewhat arenaceous	16.0
Limestone and dolomite—medium- to heavy-bedded; laminated; limestone dove-, dolomite very light-gray; thin arenaceous seams	22.0
Limestone and dolomite—medium- to heavy-bedded; fine-grained to coarsely crystalline; limestone dove and brown, dolomite light- to lead-gray; 3 inches of calcareous sandstone at base, with undulating lower contact	17.0

	FEET
Nittany Dolomite (27.5 feet)	
Dolomite—thin- to heavy-bedded; fine-grained to crystalline; laminated; basal 3 feet arenaceous	11.5
Dolomite—thin- to medium-bedded; light-gray; medium-crystalline; laminated; basal 7 feet arenaceous; lower contact undulating	16.0

CAMBRIAN

OZARKIAN SERIES (2,949.5 FEET)

Chepultepec Formation (1,047.5 feet)

NOTE: No fossils were found in this zone. It may include a Stonehenge limestone equivalent.

Limestone and dolomite—thin- to medium-bedded; fine-grained; dark- to steel-gray; limestone in majority; 6 inches of arenaceous dolomite 8 feet below top; 20 feet of thin-bedded to shaly limestone at base	71.5
Limestone and dolomite—thin- to heavy-bedded; fine-grained; dark-gray; limestone in majority; thin, oölitic limestone near middle; 2 feet of arenaceous dolomite 5 feet below top	30.0
Limestone—thin- to medium-bedded; dense to medium-grained; dark-gray; laminated; thin beds of dark-gray dolomite; thin arenaceous dolomite 3 feet below top	140.0
Poorly exposed; similar to preceding unit	490.0
Limestone and dolomite—thin- to medium-bedded; fine-grained; steel-gray to black; limestone in majority; upper 50 feet with a little black chert; 1 foot of calcareous sandstone at base	316.0

Conococheague-Copper Ridge Formation (1,652 feet)

Bloomingdale limestone member (515 feet)

Limestone—thin-bedded; fine-grained; coarsely laminated; 6 inches of arenaceous and conglomeratic limestone at base; light-gray to black, compact and oölitic chert in "float," with large *Cryptozoon*	110.0
Limestone and dolomite—thin-bedded to shaly; dark-gray; thin arenaceous dolomite 25 feet below top; a little black chert 20 feet above base; 1 foot of arenaceous limestone at base	55.0
Limestone and dolomite—thin- to medium-bedded; similar to preceding unit; much dark-gray chert; 7 thin arenaceous zones, ranging from 20 to 100 feet below top; 3 feet of calcareous sandstone at base	280.0
Limestone and dolomite—similar to two preceding units; thin arenaceous zone 18.5 feet below top; 3 feet of cross-bedded, calcareous sandstone at base	70.0

Morristown dolomite member (1,137 feet)

Limestone and dolomite—thin- to heavy-bedded; fine-grained; black to light-gray; a little oölitic texture; much black chert; thin arenaceous dolomite 40 feet below top	96.0

	FEET
Poorly exposed; similar to preceding; abundant dark-gray chert in "float," some with *Cryptozoon proliferum*	405.0
Dolomite and limestone—thin- to heavy-bedded; fine-grained; light- to dark-gray; dolomite in majority; much dark-gray chert; 3 feet of finely laminated, blue-gray limestone, with black chert, at base	248.0
Dolomite and limestone—thin- to medium-bedded; fine-grained; steel-gray to black; laminated; dolomite slightly in majority; much black chert; 6 feet of shaly limestone, with fine-textured, conglomeratic chert at base	275.0
Dolomite and limestone—similar to preceding; coarsely laminated; dolomite in majority; numerous cross-fractures; much dark-gray chert; a 2-foot arenaceous zone at base	77.0
Dolomite—thin- to heavy-bedded; fine-grained; dark-gray; numerous cross-fractures; 6 feet of thin to heavy-bedded, calcareous to quartzitic sandstone at base	36.0
Maynardville Limestone (New, 250 feet)	
Dolomite—thin- to medium-bedded; dark-gray; fine-grained; laminated; a few thin beds of limestone; several thin arenaceous zones; a little dark-gray chert	55.0
Limestone—thin-bedded to shaly; fine-grained; coarsely laminated	27.5
Dolomite and limestone—thin- to medium-bedded; fine-grained; dark-gray; laminated	27.5
Limestone and dolomite—thin- to heavy-bedded; light- to dark-gray; fine-grained; laminated; medium-textured limestone conglomerate in lower half; heavy argillaceous bands, weathering to shale	140.0
CROIXAN SERIES	
Nolichucky Shale	
Upper 150 feet: thin-bedded limestone and shale; dark-gray; greenish, drab, and yellow; with Croixan trilobites.[27]	

[27] *Acknowledgments.*—The author is grateful to Captain Walter F. Pond, State Geologist of Tennessee, for supervision, co-operation, and interest in this work; to Dr. T. E. Savage, of the University of Illinois, for encouragement and guidance; to Dr. Charles Butts, of the U.S. Geological Survey, for training in Appalachian Paleozoic stratigraphy; to Drs. E. O. Ulrich and Josiah Bridge, of the Smithsonian Institution, for valuable paleontologic and stratigraphic information; to Mr. Mark H. Newman, Chief Geologist of the American Zinc Company, Mascot, Tennessee, and Mr. Johnson Crawford, Geologist of the Universal Exploration Company, Jefferson City, Tennessee, for co-operation in the study of the Mascot and Jefferson City mines and for supplying important data; and to Dr. L. C. Glenn, of Vanderbilt University, for criticizing the manuscript.

A STUDY OF THE JOINTING IN THE FIVE SPRINGS CREEK AREA, EAST OF KANE, WYOMING

CHARLES W. WILSON, JR.
Vanderbilt University

ABSTRACT

The Bighorn Mountain uplift is thought to be a deformed wedge. This is suggested by the overturned strata, with the associated eastward-dipping thrust fault, along parts of the western flank and the previously recognized steep dips, with the associated westward-dipping thrust faults, of the eastern flank. The joints in the pre-Cambrian granite exposed along Five Springs Creek may be grouped into ten sets of original pre-Cambrian joints and two secondary sets that were formed by the Laramide orogeny. Using the data obtainable from the original structures in the granite, it is possible to determine the direction of the compressive stresses that governed the intrusion. This information permits the study of the origin and interpretation of the original joints in relation to these stresses. It is believed that the following systems of original joints were formed during different stages of the intrusion: (1) System *A*, stage of initial intrusion, but overlapping the following two later stages; (2) System *B*, stage of predominant lateral spread; and (3) System *C*, stage of predominate vertical bulging that took place as the granite approached its maximum limits of lateral spread. The two secondary sets were formed during the Laramide orogeny by differential movement between joint blocks bounded by pre-Cambrian original joints.

INTRODUCTION

During the summer of 1932 the writer joined the group of geologists which has been carrying forward a comprehensive program of geological research work in the Yellowstone-Beartooth-Bighorn region of Montana and Wyoming,[1] headquartering near Red Lodge, Montana. As part of this program a very detailed planetable map was made of an area of about 7 square miles in Bighorn County, Wyoming. This area is located several miles east of Kane, where the Kane-Dayton Highway ascends the western front of the Bighorn Mountains, the highway in this locality following the course of Five Springs Creek.

Professors W. H. Bucher, R. T. Chamberlin, and W. T. Thom, Jr., had previously found the eastward-dipping thrust plane at this locality and had also recognized the possibilities that might result from a study of the joints in the granite. It was at their suggestion that the field work was done, and to them the writer wishes to ex-

[1] W. T. Thom, Jr., and R. M. Field, "The Advancement of Geology through Co-operative Research," Sci., Vol. LXXII (Aug. 1, 1930), pp. 117–18; W. H. Bucher, W. T. Thom, Jr., and R. T. Chamberlin, "Geologic Problems of the Beartooth-Bighorn Region," *Geol. Soc. Amer.*, Vol. XLIV (1933), pp. 75–77.

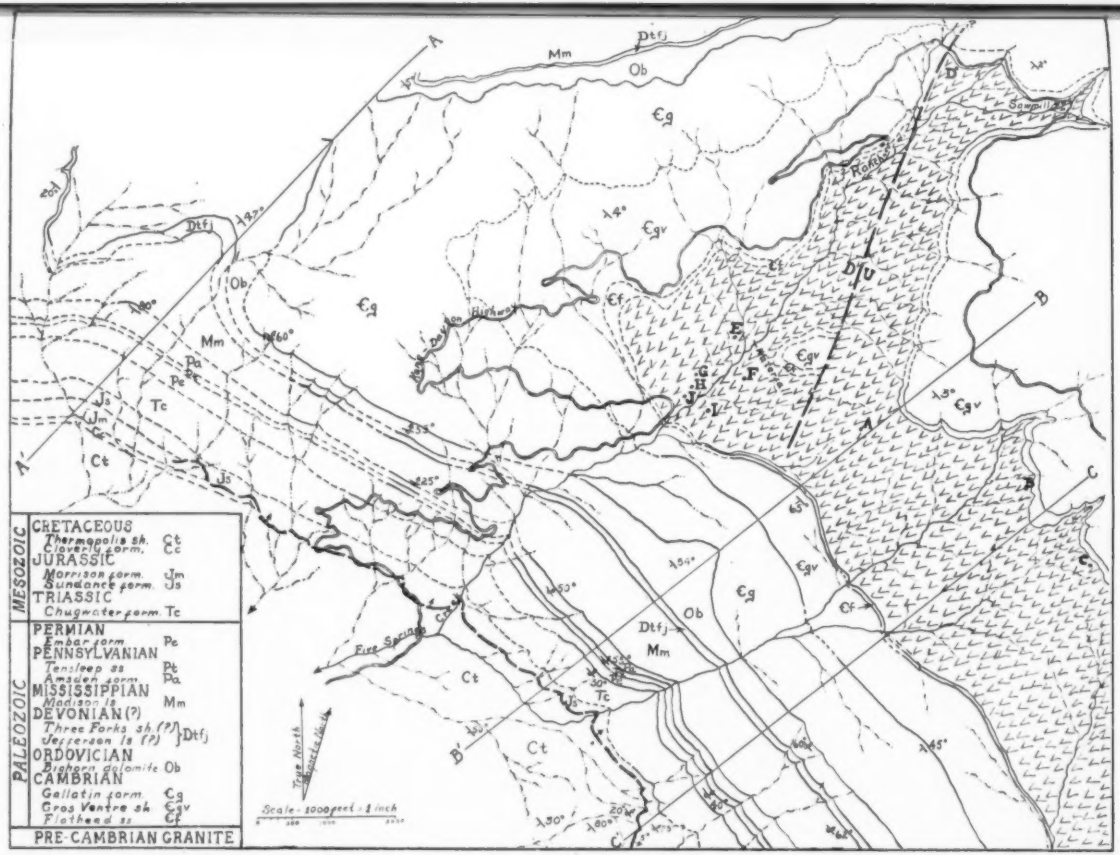


FIG. 1.—Geologic map of the Five Springs Creek area along the Kane-Dayton Highway where it ascends the western front of the Bighorn Mountains several miles east of Kane, Wyoming.

press his gratitude for suggesting the possibilities of the problem and offering practical suggestions in the field.[2]

STRATIGRAPHY

The consolidated rocks exposed within the area mapped range in age from pre-Cambrian to Cretaceous. All of the intervening systems, with the exceptions of the Silurian and possibly the Devonian, are represented. The different formations present are listed in the

TABLE I

SECTION OF FORMATIONS IN THE FIVE SPRINGS CREEK AREA, WYOMING

	Feet
Cretaceous:	
Thermopolis shale	Full thickness not exposed
Cloverly formation	Full thickness not exposed
Morrison formation	Full thickness not exposed
Jurassic:	
Sundance formation	210
Triassic:	
Chugwater formation	650
Permian:	
Embar formation	65
Pennsylvanian:	
Tensleep sandstone	40
Amsden formation	165
Mississippian:	
Madison limestone	920
Devonian (?):	
Three Forks shale (?)	25
Jefferson limestone (?)	110
Ordovician:	
Bighorn dolomite	270
Cambrian:	
Gallatin limestone	450
Gros Ventre shale	457
Flathead sandstone	42
Pre-Cambrian:	
Coarse-grained, grayish-red granite with a few small inclusions of a much altered basic rock cut by thin pegmatites	

[2] To Professor Bucher the writer is especially indebted for his valuable aid in the interpretation of the joints and in the preparation of several of the figures. Professors W. H. Bucher, A. F. Buddington, R. T. Chamberlin, L. C. Glenn, W. B. Jewell, and W. T. Thom, Jr., kindly read the manuscript and offered helpful criticism. Mr. Eric Bucher, of Cincinnati, Ohio, efficiently assisted the writer in making the planetable map.

following paragraph. For general descriptions the reader is referred to two publications on this region by Darton.[3]

STRUCTURE OF THE AREA

The Bighorn Mountains consist of a large, compound uplift that arose out of the nearly flat-lying strata of the surrounding plains during the Laramide orogeny. On the top of this major uplift the remnants of sedimentary strata are almost flat. Along the flanks of the uplift, however, the gently dipping strata are abruptly flexed downward. For a detailed description of the structure of the Bighorn Mountains the reader is referred to Darton's reports.[4]

The western flank of the north end of the Bighorns is formed by steeply flexed monoclines rising abruptly out of the nearly horizontal strata of the Bighorn basin and flattening out into the almost horizontal strata on the top of the major structure. The type of structure common to this portion of the Bighorns is indicated by the structural cross section along the line A–A' (Fig. 3).

Near the area mapped, the general, steeply dipping monocline passes into an overturned flexure; and this is, in turn, broken by a thrust fault dipping to the northeast (Sec. B–B' and C–C', Fig. 3). This fault extends along its strike for a minimum distance of approximately $3\frac{1}{2}$ miles and has a maximum heave of more than 600 feet. The fault plane is best exposed in the south-central part of the map near C'. At this locality the greenish-gray shale of the Sundance formation, which is overturned 70°, has been thrust over the black Thermopolis shale, which is similarly overturned about 70°. This abrupt change in color along the fault plane is plainly visible from the highway. The dip of the plane at this locality is only 5°. Probably, however, the average dip of the plane is greater.

Attention might be called here to the cross section along the line C–C'. One may climb up the mountain front along this line and pass through a reversed sequence of overturned strata from the Cretaceous to the Cambrian, with the exception of the Silurian and possibly the Devonian. The axis of the overturned and faulted flexure

[3] N. H. Darton, *U.S. Geol. Surv. Geol. Atlas, Bald Mountain–Dayton Folio No. 141* (1906), pp. 2–8; "Geology of the Bighorn Mountains," *U.S. Geol. Surv. Prof. Paper 51* (1906), pp. 13–65.

[4] "Geology of the Bighorn Mountains," *op. cit.*

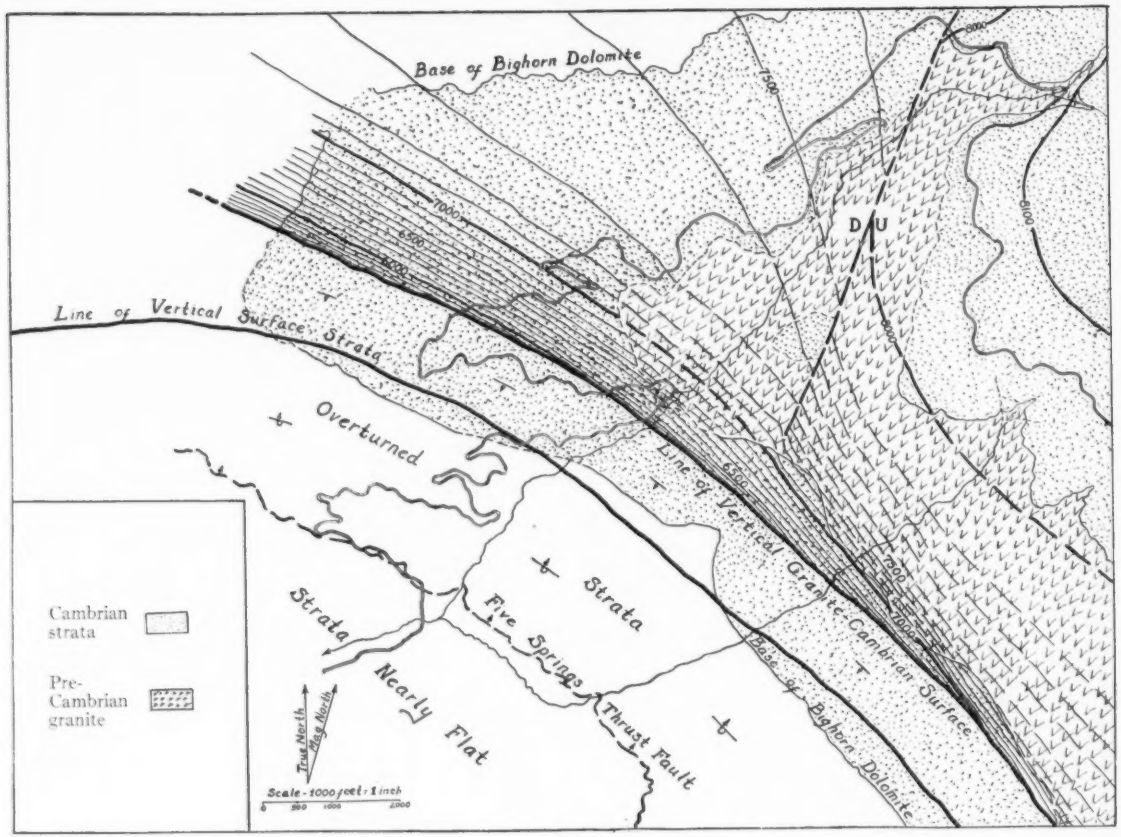


FIG. 2.—Structure contour map of the Five Springs Creek area. The structure contours are drawn on the top of the granite and represent the present structural position of the pre-Cambrian erosional surface.

comes to the surface along this section near the middle of the Gallatin limestone.

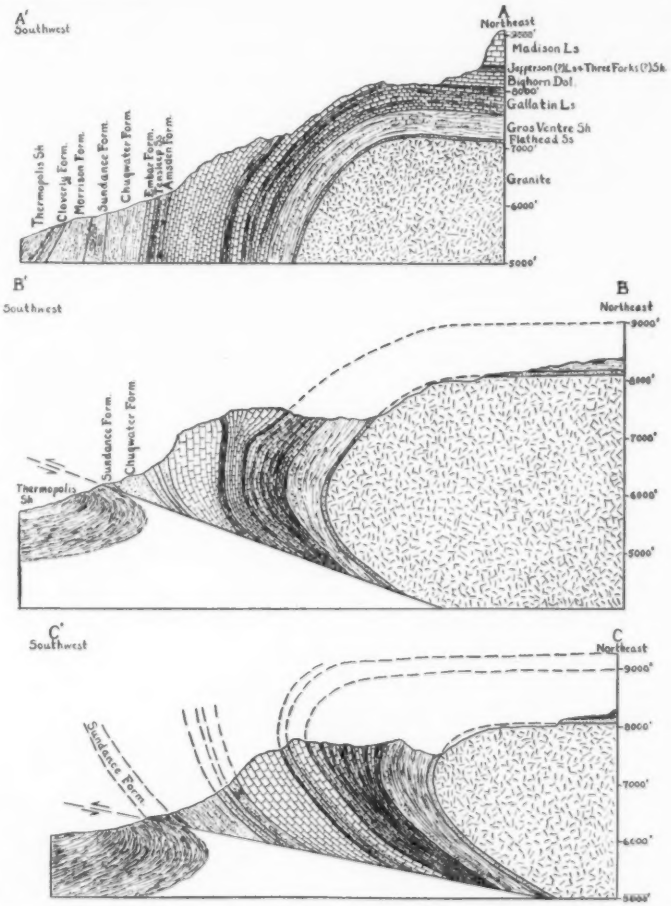


FIG. 3.—Structural cross sections across the map (Fig. 1) along the lines *A'–A*, *B'–B*, and *C'–C*. Natural scale, 1 inch to 1,000 feet.

FIG. 2.—Structure contour map of the Five Springs Creek area. The structure contours are drawn on the top of the granite and represent the present structural position of the pre-Cambrian erosional surface.

OVERTHRUSTING VERSUS UNDERTHRUSTING

As to whether this fault is an overthrust or an underthrust, the writer hesitates to commit himself. At the northwestern extremity

of the fault, where it passes into an unbroken, steeply dipping monocline, it is found by the writer, using Lovering's[5] criteria, that the strike of the strata swings abruptly to the west, or toward the Bighorn basin. This swing is much more obvious in the field than it is on the accompanying map, as the entire change of strike is not included within the mapped area (line of vertical surface strata, Fig. 2).

A change of strike of this type suggests that the drag[6] produced by the active footwall is thrust under the relatively passive hanging wall, or Bighorn Mountain block. On the basis of this evidence the fault is an underthrust.

WEDGE THEORY OF DIASTROPHISM

A significant feature of this fault is its apparent kinship to the type of structure demanded by the wedge theory of diastrophism.[7] As stated before, the Bighorn Mountains consist of a large, elongate uplift with flat or gently dipping strata on the top, and with steep, monoclinal dips along its flanks. Locally, as seen on the subsurface structural contour map[8] in Darton's report, the flanks are oversteepened and locally faulted. This oversteepening and faulting predominates on the eastern flank and extends from Dayton southward to Mayoworth. On the western flank the oversteepening and faulting is limited to the northern end of the structure, extending from near Shell northward to the Montana-Wyoming state line. This general relationship is highly suggestive of wedge dynamics.

The origin of the Bighorn structure, however, is not attributed by the writer to the wedge theory of rigid crustal deformation only, for more plasticity of the subcrust is accepted than might be assumed under the wedge theory, if applied alone. As Thom[9] has stated: "In the writer's opinion such uplifts as the Bighorns . . . . are produced not by simple folding under compression or by the iso-

[5] T. S. Lovering, "Field Evidence To Distinguish Overthrusting from Underthrusting," *Jour. Geol.*, Vol. XL (1932), pp. 651–63.

[6] *Ibid.*, p. 655.

[7] R. T. Chamberlin, "The Wedge Theory of Diastrophism," *Jour. Geol.*, Vol. XXXIII (1925), pp. 755–92.

[8] "Geology of the Bighorn Mountains," *op. cit.*, Plate 37.

[9] "The Relation of Deep-seated Faults to the Structural Features of Central Montana," *Bull. Amer. Assoc. Petr. Geol.*, Vol. VII (1923), p. 5.

static adjustment of areas of deficient mass, but are the products of a combination of the two processes. . . . ."

This permits the combining of two recognizably potent factors. First are the tangential compressive stresses transmitted in competent outer rocks ("zone of fracture"), productive of the general wedge shape of the structure. And second are the deeper stresses transmitted plastically in the "zone of flow," responsible for the elevation of the mountain wedge and for the monoclinal draping of the sedimentary beds along the margins of the elevated blocks.

NORMAL FAULTING

The normal fault in the northeast corner of the map is a pronounced structural and topographic feature. This fault strikes about N. 18° E. and has a maximum downthrow of about 400 feet to the west. The highway, from where it leaves Five Springs Creek just below the waterfall up to the ranch shown on the map, is not far above the top of the granite. Across the Creek, however, is a vertical scarp where the top of the granite is several hundred feet higher.

JOINTS

The joints studied in this report are all in the pre-Cambrian granite exposed by Five Springs Creek and its tributaries along the axis of flexure in the oversteepened monocline which has been ruptured by the Five Springs thrust fault. Most of these joints are exposed in the steep walls of the canyon of the main creek, which has been cut about 400 feet into the granite.

Stations A, B, C, D, and E were chosen northeast of the axis of this flexure for the purpose of studying the joints at localities relatively unaffected by local torsional stresses resulting from the development of the Five Springs thrust fault during the Laramide revolution. At these stations, which are close to the cover of Cambrian sediments, the strikes and dips of the joints are, in all likelihood, approximately the same as they were at the beginning of the Cambrian period. These stations are distributed over a distance of about 6,000 feet parallel to the strike of the Five Springs thrust.

Southwest of the axis of the Five Springs flexure Stations F, G, H, I, and J were located along the walls of the canyon of Five Springs

Creek. These stations (Fig. 4) were chosen at localities at which different degrees in the increased dip, or bend, of the flexure were observable. At these stations the strikes of the joints have been more or less rotated either clockwise or counter-clockwise, and the dips increased or decreased depending upon the attitude of the joints in relation to the flexure.

At each station the strike and dip of well-developed joints within a radius of about 20 feet were measured by the writer. No attempt was made to group the joints into sets at the time they were measured, as such preliminary grouping undoubtedly would have influenced the writer in choosing or eliminating joints for measurement.

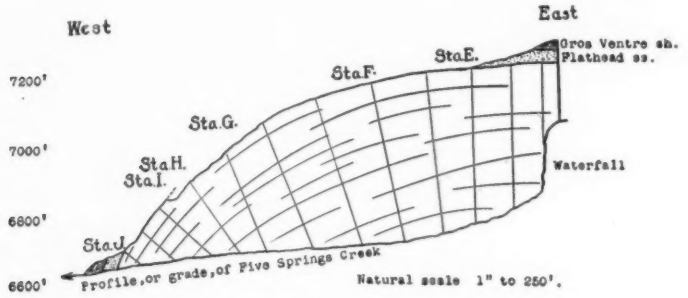


FIG. 4.—Diagrammatic cross section along the canyon of Five Springs Creek, showing the effect of the Laramide orogeny upon the joints of *A-2* (horizontal sheeting) and *B-4* (strike N. 48° W. and hence almost parallel to the strike of the flexure).

When all the strikes and dips of these joints are plotted (Fig. 5), they appear, at first sight, to range indiscriminately through all the points of the compass. Observation in the field, however, revealed definite patterns; and closer inspection of the charts shows, likewise, that without doing violence to the data, they can be grouped into ten sets of original joints which bear definite relations to the principal stresses that may be inferred from the primary structure of the granite. By taking into account the degree of development of the joints and their distribution (whether local or general) and their mutual relations as seen in the field, a satisfactory interpretation can be given for their origin.

The charts in Figure 5 are polar projections which represent the

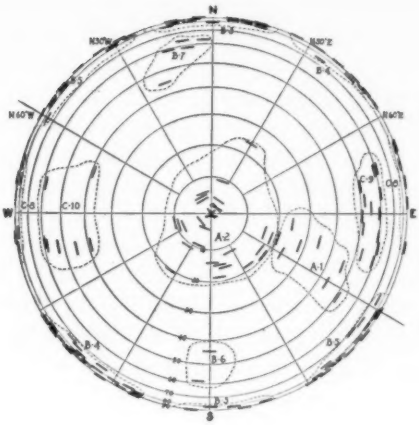


FIG. 5*a*

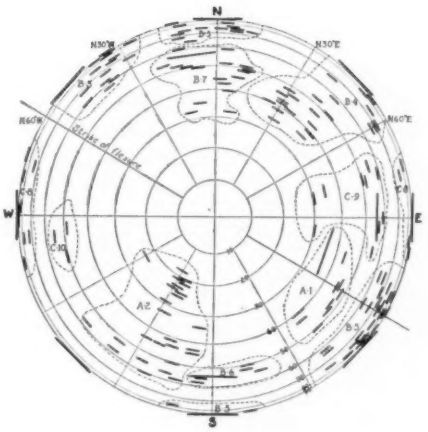


FIG. 5*b*

FIG. 5*a*.—Polar projection of the strike of the joints measured northeast of the flexure. The strike and dip of these joints were not affected by the Laramide orogeny.

FIG. 5*b*.—Polar projection of the strike of the joints measured southwest of the flexure. The strike and dip of these joints were affected to varying degrees by the Laramide orogeny. The heavy strike lines represent the average of each set taken from 5*a*.

equatorial plane of a sphere, the eye being placed at infinity parallel to the axis. The pole of this projection is the intersection of the axis and the sphere, and the periphery is the intersection of the equatorial plane and the sphere. Upon this plane of projection the strike of each joint has been plotted. The joints are plotted as dipping away from the pole. A joint on the periphery is vertical, and one at the pole is horizontal. The distance of the strike-line from the pole varies inversely with the dip of the joint.

Chart A (Fig. 5) shows the projection of the strikes of all the joints measured northeast of the flexure, and includes only those joints the strikes and dips of which were unaffected by the Laramide orogeny. These original joints fall into the sets shown in Table II.

TABLE II

	Average Strike	Average Dip
A*-1	N. 21° E.	37° SE.
A-2	Irregular	0°–20° in any direction
B-3	E.-W.	Vertical
B-4	N. 48° W.	Vertical
B-5	N. 45° E.	Vertical
B-6	E.-W.	54° S.
B-7	N. 83° E.	56° N.
C-8	N.-S.	Vertical
C-9	N.-S.	56° E.
C-10	N. 5° W.	49° W.

* Reference to the Systems A, B, and C will be made in the interpretation of the origin of the joints.

Chart B (Fig. 5) shows the projection of the strikes of the joints measured southwest of the flexure. The effect of the Laramide orogeny upon the strikes and dips of the original pre-Cambrian joints affected by this orogeny is best seen by comparing the sets shown on Chart B with the corresponding sets on Chart A. These comparisons, given in the following paragraphs, explain the variations of these joints from the average, undisturbed strikes and dips northeast of the flexure (Chart A). As sets A-1, B-3, B-5, B-6, C-8, and C-10 were relatively unaffected, they will be omitted from the following summaries of the effects of the orogeny upon certain of the sets.

A-2, Strike.—Northeast of the flexure the strikes and dips of the sheeting joints are extremely variable; whereas southwest of the flexure the strike and the direction of dip are controlled by the bend-

ing of the flexure. The resulting strike of the sheeting is approximately parallel to the axis of the flexure, and hence gives an important clue as to the true strike of the axis.

Dip.—The degree of dip to the southwest gradually increases from 18° to the exposed maximum of 60°.

B-4, Strike.—As the strike of this set is roughly parallel to the axis of the flexure, the strike was not affected.

Dip.—The northeast dip, however, gradually changes from perpendicular to a minimum of 35° following the degree of dip, or bend, of the flexure.

B-7, Strike.—The strike has been relatively unaffected.

Dip.—The dips to the north are lower than they originally were.

C-9, Strike.—The strike has been relatively unaffected.

Dip.—The dips are lower to the east than they originally were.

PRIMARY STRUCTURE OF THE GRANITE

To make possible an interpretation of the relationship between the different sets of joints and the axis of causal stress, it was necessary to examine all the original structures in the granite which might aid in the determination of the original orientation of the intrusive body. To accomplish this aim, the methods so successfully initiated by Cloos,[10] and subsequently used by others, were followed. These methods have been described by Balk.[11]

The granite is commonly homogeneous in structure, showing no apparent orientation. At certain localities, however, inclusions of basic igneous rock, schlieren, zones of oriented minerals, and gneissic bands furnish sufficient evidence to determine the direction of stretching (*Streckungsrichtung*), or the "direction of escape" (*Ausweichrichtung*). This is the rift, or "easyway," of quarrymen.

The inclusions in the granite consist of greatly altered, basic, igneous rock. In size the inclusions vary from blocks 5×30 feet, as seen in a two-dimensional section, to the schlieren, or slight flow bands of the basic rock in the granite. Many of the inclusions are blocks that average about 6 inches in width and about 2 feet in length.

[10] Hans Cloos, "Tektonik und Magma," Untersuchungen zur *Geologie der Tiefen* (herausgegeben von H. Cloos) (1922).

[11] Robert Balk, "Primary Structure of Granite Massives," *Geol. Soc. Amer. Bull. 36* (1925), pp. 679–96.

The blocks of inclusions are all unequidimensional in accordance with an original, gneissic structure within the inclusion. The unequidimensional inclusions are all oriented with their greatest dimension parallel to the direction of stretching. This means that the original, gneissic structure inherent in the basic rock before it was intruded by the granite, the plane of greatest dimensions of the un-

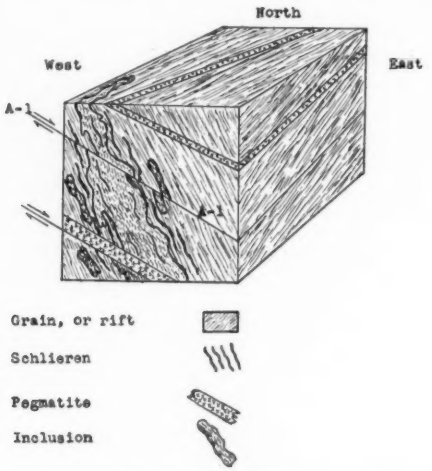


FIG. 6.—Diagrammatic block showing the rift, schlieren, pegmatites, inclusions, and the marginal joints of System *A*, Set 1, found in the granite. This block was drawn from data collected at Station *E*.

equidimensional inclusions, and the direction of the schlieren, or flow bands, in the granite are all subparallel and at any one locality all dip in the same direction at approximately the same degree.

The data from a few of the inclusions are as follows:

Station A

Strike of Inclusion	Dip
N. 30° E.	Vertical
N. 32° E.	Vertical

Station E

N. 10° E.	54° E.
N. 10° E.	62° E.
N. 22° E.	56° E.

Slight bands of light and dark minerals are seen at different localities in the granite, and especially in the immediate vicinty of an inclusion. These are the schlieren. The orientation of this structure is as follows:

Station E

Strike	Dip
N. 21° E.	60° E.
N. 10° E.	55° E.
N. 15° E.	55° E.

Upon examination, far the larger part of the granite shows no apparent orientation of individual crystals. In certain localities, however, the orientation of feldspar and amphibole crystals can be determined clearly and measured. At station E several measurements were made. The strike of the orientation there varied between N. 21° E. and N. 30° E. Also, at the same station a 17-inch zone of granitic gneiss was found. This zone strikes N. 20° E. and dips 30° E.

Average Strikes of the Stretching Structures

Inclusions	N. 21° E.
Schlieren	N. 15° E.
Oriented minerals	N. 27° E.
Gneiss	N. 20° E.

The composite strike of these stretching structures at Stations A and E is N. 20° E. The planes of stretching are vertical at Station A, but at Station E they have an average dip of 58° E.-SE.

In the immediate vicinity of Station E eight pegmatite dikes were found. The dikes consist of a coarse, crystalline variety of the granite and cut sharply across both the granite and the basic inclusions. The thickness of the dikes ranges from 2 inches to 16 inches. The average strike of the pegmatites is N. 29° E., but varies between N. 15° E. and N. 37° E. The average dip is 30° E.-SE., but varies from 20° to 58°.

All of the pegmatite dikes studied at this Station were intruded along the "marginal joints" (System A, Set 1). The joints are known to occur near the margin of an intrusive body and dip toward the center of the body.[12] The last magma remaining liquid was squeezed as dikes along the more or less open tensional joints, dipping toward the center of the intrusion.

[12] Balk, *ibid.*, p. 688.

In this respect the granite intrusive body of the Bighorn Mountains, as exposed in the area mapped, differs from the majority of those studied by Cloos, Balk, and others. The dikes in the other intrusions have been known to occur principally in the tensional joints formed parallel to the axis of compressive tectonic stress and perpendicular to, or crossing, the direction of stretching. In the area studied, however, all the dikes seen by the writer had been intruded along marginal joints and none along the tensional joints normal to the stretching. The difference in the occurrence of the dikes does not conflict in any way with any principle involved, as the magma, which later crystallized to form the dikes, could have been intruded into either set of joints equally well, depending upon local or regional factors that determined which set presented the optimum conditions for intrusion of the dikes.

After its crystallization, ten sets of original joints were developed in the granite. These, however, will be taken up in detail.

AXIS OF PRE-CAMBRIAN TECTONIC STRESS

From the evidence of the stretching structures, which have an average strike of N. 20° E., one is led to assume that the axis of tectonic stress which sponsored the intrusion of the granite, acted at about 90° to this strike, or N. 70° W. In face of the overwhelming evidence, however, of the original joint systems—the vertical tensional joints normal to the stretching, the two sets of vertical shearing joints at 45° to the axis of causal stress, and the set of vertical joints which forms normal to the tensional joints, etc.—one must conclude that the tectonic stress actually acted in an east-west direction rather than N. 70° W., as suggested by the stretching structures.

This discrepancy may be explained by one of two possible postulates, of which the second is regarded as more plausible by the writer. The first of these is that the actual intrusion, and hence the development of the stretching phenomena, took place under the influence of stresses acting N. 70° W. At some time during or following the intrusion the axis of causal stress shifted from N. 70° W. to E.-W. This would have permitted the joint systems to have been formed under the influence of an E.-W. stress.

The second is that this particular locality (Five Springs Creek) along the contact of the pre-Cambrian country wall-rock and the intrusion was the southern limb of a salient of the wall-rock into the granite, or on the northern limb of a salient of the granite into the wall-rock. Such irregularities of outline of an intrusion of this type are common. Although the stretching structures parallel the irregular outline of the body, the orientation of the joints is the result of more than the influence of local factors of this kind and maintains more or less the same strike throughout the entire body, regardless of irregularities of outline.

SECONDARY STRUCTURES

All of the structures thus far discussed are original structures resulting from the tectonic stresses that sponsored the intrusion of the granite at some time during the pre-Cambrian. At some later date before the Cambrian, the region was subjected to erosion that resulted in the uncovering and exposure of a large area of the granite. The seas of the Paleozoic spread over the top of the truncated intrusion and deposited their sediments. During the Mesozoic era deposition of both marine and terrestrial sediments continued. Beginning in the latter part of this era, tectonic stresses of the Laramide orogeny caused the uplift of the Bighorn Mountains. Erosion subsequent to this orogeny has been able to cut through the Paleozoic and Mesozoic sediments in places and to expose the underlying granite where favored by structural position.

The flexure associated with the Five Springs thrust, which has been described previously, was an important factor in the secondary accentuation of the original pre-Cambrian joints and in the development of two, new sets of secondary joints. It seems highly improbable to the writer that an entirely new series of joints could be superimposed upon the original systems by the later deformation if the pre-existing systems of joints would satisfy most of the strain demands of the secondary stresses.

All the internal movement, or rearrangement, required of the granite in response to the Laramide orogeny, it is believed by the writer, was accomplished along the different sets of original joints. Movement took place along the large number of closely spaced joints in

such a way that movement along one joint plane was small, but the total amount large. This is demonstrated by the fact that practically every joint surface of any block of granite one may pick up has been slickensided until the surfaces feel perfectly smooth. These slickensided joint blocks are quite small, many being reduced to slabs $\frac{1}{2}$ inch in thickness. The size of the blocks of granite bounded by slickensided surfaces approach the dimensions of blocks, or slabs, produced by fracture cleavage. Especially is this true of the granite at the stations where the greatest degree of bending has taken place. It should be understood that the deformation of the granite occurred under a cover of only about 10,000–14,000 feet.

The belief that movement was distributed over original joint surfaces was likewise substantiated by the study of thin sections which were cut from oriented hand specimens. The specimens had been chosen in the field on the basis of their relationship to the sets of joints. The thin sections showed no evidence of recrystallization, rotation, granulation, or gliding that would be in evidence in case the granite had actually "flowed," in any sense of the word. The only suggestion of internal deformation of the granite was the slightly wavy extinction, or strain shadows, in about half the quartz grains, which suggests only slight internal deformation.

This secondary deformation of the granite along its sets of original joints also caused a high degree of development of all incipient, or potential, joints paralleling any of the major original joint sets. Similarly, the secondary deformation caused the unequally developed original sets of joints to appear today as all being more or less equally developed.

It is the remarkable development and abundance of the joints that attracts the student to this locality. Practically every visible surface of any granite fragment, regardless of how large or how small, is a joint surface. The spurs along the walls of the canyon of Five Springs Creek resemble castles studded with turrets.

AXIS OF LARAMIDE TECTONIC STRESS

The axis of the Five Springs flexure, which was produced by the Laramide orogeny, as previously stated in the discussion of structure, strikes N. 60° W. within the area mapped. This implies that the stresses which produced this structural feature acted approximately N. 30° E.

From the complete lack of agreement between the axis of the Laramide tectonic stresses (N. 30° E.) and the strikes of the different sets of joints (Table 2) it is definitely known that ten sets of joints did not result from Laramide stresses. For this reason, and also because of the close agreement of the joints to the original structures in the granite, it is known that these sets of joints are original joints resulting from pre-Cambrian stresses.

INTERPRETATION OF THE ORIGIN OF THE JOINTS

The interpretation of the origin of twelve sets of joints formed within the same body presents its own difficulties. The difficulties were increased by the Laramide orogeny, which, with one exception, destroyed all possible trace of any offset of one set by another. Because of this, there were few available data as to the chronological development of the joints.

Sets and systems of joints in intrusive bodies have been described from a large number of localities. But the writer knows of no instance in which an interpretation has been given for any joints, with the exception of the vertical tensional, "cross," or "*Q*," joints[13] that are normal to the direction of stretching; the vertical joints parallel to the direction of stretching, the "*S*" joints; and the marginal tensional joints, or "Streckflächen," which dip into the body at moderately low angles.

The interpretation of the following different sets of joints is the result of a study of the related principles as presented by Bucher,[14] Cloos,[15] Balk,[16] Paige,[17] Chamberlin and Link,[18] and others.

SYSTEM A

FIRST PERIOD OF JOINT DEVELOPMENT

Set 1

Average strike*..... N. 21° E.
Average dip..... 37° SE.

* The average strike and dip given for each set refers only to those measurements made northeast of the flexure.

[13] Cloos, *op. cit.*, p. 5. [14] Personal communication. [15] *Op. cit.*

[16] *Op. cit.; idem* "Geology of the Newcomb Quadrangle," *N.Y. State Mus. Bull. No. 290* (1932).

[17] Sidney Paige, "The Bearing of Progressive Increase of Viscosity during Intrusion on the Form of Laccoliths," *Jour. Geol.*, Vol. XXI (1913), pp. 541–49.

[18] R. T. Chamberlin and T. A. Link, "The Theory of Laterally Spreading Batholiths," *Jour. Geol.*, Vol. XXXV (1927), pp. 319–52.

This set, the "Streckflächen" of Cloos, is composed of the marginal tensional joints that occur near the margin of the intrusive body and dip into the granite. In the area mapped, these joints have an average dip of 37° SE.

It is along this set of joints that the intrusion of the pegmatite dikes took place. For this reason and also from their general mode of occurrence, it is believed that this was the first set of joints to form. The joints were formed at a stage in the cooling and crystallizing of the intrusion when upward movement of the highly viscous magma produced secondary tensional stresses in the previously crystallized outer portion of the intrusive body near the contact with the rigid, country wall-rock.

Continued intrusion resulted in differential movement between the blocks bounded by this initial set of joints. Because of this movement, most of the joints of this set became low-angle normal faults with small displacements. The joints, or low-angle normal faults, offset the basic inclusions, schlieren, etc., and are in turn clearly cut by all the other sets of joints (Fig. 6).

Set 2

Average strike	Irregular
Average dip	0°–20° in any direction

This set includes the irregular, horizontal sheeting joints which form the "lift" of quarrymen. The writer's experience with this commonly developed set of joints has been too limited to warrant an expression of opinion on their origin. It seems somewhat doubtful, however, that they were formed by external stresses. Dr. W. H. Bucher suggested to the writer that ". . . . the joints were probably due to internal stresses arising from shrinkage incident to cooling."

It may be possible that the development of this set of joints was aided later by vertical tensional stresses acting perpendicular to the lateral axis of greatest compressive stress. If this is true, the accentuation of the joints in this manner took place during the stages of intrusion when relief was easier upward (second stage of intrusion).

SYSTEMS B AND C

In order to understand the reasoning underlying the interpretation of the two systems of joints, it is necessary to review certain gen-

eral principles of intrusion. It will be assumed that this granite was intruded as a batholith. It may be, however, that it was closely kin to the "pseudobatholith" type referred to by Balk.[19] The writer cannot be definite because he has seen too little of the granite exposed in the Bighorn Mountains.

Paige[20] has described a series of intrusive bodies that represent a sequence followed during the intrusion of a single laccolithic body. The sequence begins with the lateral spread, or extension, of a more or less flat sheet of magma, as represented in static form by the Shonkin Sag. As the magma approaches its limits of maximum, lateral extent, the continuous introduction of more magma from beneath causes the more or less previously consolidated body to bulge upward. In such cases the approach to the limits of lateral spread is caused by increasing viscosity which precedes crystallization. This stage is represented by Crow Peak of the Black Hills and certain laccoliths of the Judith Mountains, Montana.

Small batholiths, and especially pseudobatholiths, are known to intergrade with laccoliths.[21] Hence, the writer concludes from the homologous relationship of batholiths and laccoliths and from the evidence presented by the sets of joints, which are present in the area under discussion, that there are similarly two major stages in the intrusion of such a batholith.

The first of the two stages is characterized by predominantly lateral extension of the magma. The lateral spread continues until its limits of maximum extent are approached. These limits would be controlled by the chilling of the thin edges of the magma and by the resistance offered to the spread, which is controlled by the tectonic stresses sponsoring the intrusion of the magma. During this stage, lateral relief generally would be easier than upward relief. The direction of relief would be in accord with the stretching component resolved within the body perpendicular to the axis of greatest stress and parallel to the direction of increasing lateral elongation.

The joints of System *B*, it is believed by the writer, would be formed during this stage after cooling and crystallization of all of the magma with the exception of that near the area of continued introduction.

[19] *Op. cit.*, p. 689. [20] *Op. cit.*, p. 545. [21] Chamberlin and Link, *op. cit.*, p. 343.

As the magma, which is now more or less consolidated, has reached its limits of maximum extension, further continuous introduction of magma from beneath would cause the intrusion to bulge upward. This, the second stage, is characterized by easier upward relief and by tensional stresses which are developed in the upward-bulging intrusive body. The writer believes that the joints of System *C* were formed during this stage.

It must be understood that the change from the first to the second tage is gradational and that no definite limits may be drawn. This somewhat theoretical conception possibly may be proved incorrect, but in the opinions of Professor Bucher and the writer it furnishes the most plausible explanation of the origin of the joints. The writer invites the application of this conception to other similar intrusives where more is known and where other lines of evidence are available.

SYSTEM B

SECOND PERIOD OF JOINT DEVELOPMENT

Set 3

Average strike	E.-W.
Average dip	Vertical

The vertical tensional joints are formed parallel to the axis of greatest stress and are parallel to the "hardway" of the granite. They are the "*Q*" joints of Cloos. They cross the stretching structures perpendicularly. The formation and orientation of such joints indicate easy lateral (north-south) relief in response to the elongation of the intrusive body normal to the tectonic stress (Fig. 7*a*).

Set 4

Average strike	N. 48° W.
Average dip	Vertical

Set 5

Average strike	N. 45° E.
Average dip	Vertical

The two sets of joints comprise a pair of vertical shearing joints formed at approximately 45° to the east-west axis of causal stress. Their formation is indicative that the north-south lateral relief is easier than upward relief (Fig. 7*a*).

Set 6

Average strike	E.-W.
Average dip	54° S.

Set 7

Average strike	N. 83° E.
Average dip	56° N.

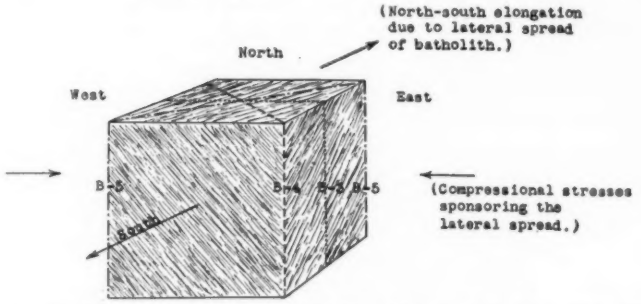


FIG. 7*a*.—Diagrammatic block showing joints of System *B*, Sets 3, 4, and 5. These joints were formed under the influence of east-west compressive stresses and north-south elongation. General conditions.

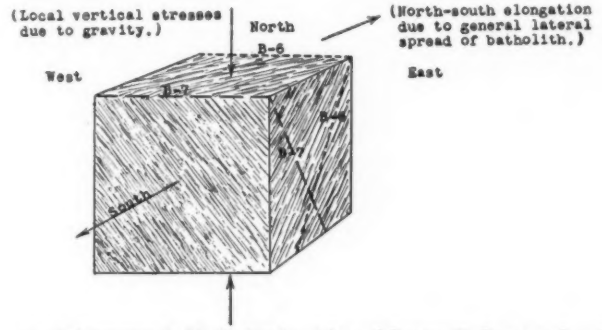


FIG. 7*b*.—Diagrammatic block showing joints of System *B*, Sets 6 and 7. These joints were formed locally under the influence of local vertical stresses that resulted from load, or gravity, and also under the influence of north-south elongation.

The joints comprise two sets of oblique shearing joints which strike parallel to the axis of greatest stress. They are neither abundant nor uniformly distributed. Their distribution suggests development only at certain localities. A strong factor in their limited development would be local, vertical compressive stress. Cloos[22] speaks

[22] *Op. cit.*, p. 4.

of a struggle between pressure and load, or gravity (*"Wettstreit zwischen Druck und Last"*), which implies that during the intrusion of a body there is a struggle for local supremacy between the lateral tectonic stress governing the intrusion and the vertical compressive stress, or gravity.

The former usually prevails in such conflicts. At certain localities, however, gravity may dominate, at least for a sufficient length of

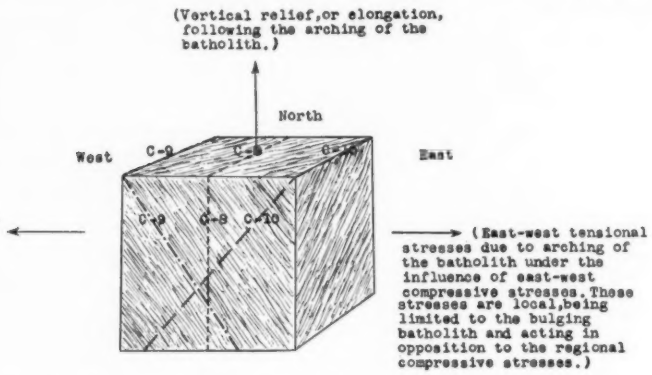

(Vertical relief,or elongation, following the arching of the batholith.)
North
West
East
C-9
C-8
C-10
(East-west tensional stresses due to arching of the batholith under the influence of east-west compressive stresses. These stresses are local,being limited to the bulging batholith and acting in opposition to the regional compressive stresses.)

FIG. 8.—Diagrammatic block showing joints of System *C*, Sets 8, 9, and 10. The joints of Sets 9 and 10 were formed under the influence of east-west compressive stresses and upward relief, or elongation. Joints of Set 8 were formed by secondary tensional stresses (east-west elongation) in very much the same manner as tensional joints are formed along the crest of an anticline.

time for the local development of the two sets of joints. The resulting local joints would be oriented east-west, because during this stage the direction of greatest relief, or elongation, would be north-south. The lateral elongation, or stretching, even might be a factor in the formation, as well as the orientation, of the joints (Fig. 7*b*).

SYSTEM C.

THIRD PERIOD OF JOINT DEVELOPMENT

Set 8

Average strike	N.-S.
Average dip	Vertical

This set of joints, the "*S*" joints of Cloos, was formed perpendicular to the axis of causal stress and roughly parallel to the rift, or direction of stretching.

It has been stated in the foregoing that during the second stage of intrusion (third period of joint development) tensional stresses resulted from the upward bulging of the intrusive body. Such tensional stresses would open a set of joints (C-8) in very much the same manner as tensional joints are formed along the crest of an anticline and parallel to its axis (Fig. 8).

In this particular region another much later factor in the development of the set cannot be overlooked. At the time of the origin (pre-Cambrian) of C-8 and B-3, the regional compression was about E.-W. At the time of the Laramide orogeny the compression was directed N. 30° E. It is apparent from the comparison that the directions of C-8 and B-3 were used during the Laramide orogeny as directions of vertical shearing at approximately 45° to the axis of causal stress.

Set 9

Average strike	N.-S.
Average dip	56° E.

Set 10

Average strike	N. 5° W.
Average dip	49° W.

The two sets are oblique shearing joints that strike perpendicular to the axis of causal stress, or parallel to the direction of stretching, and dip at a slightly obtuse angle to this axis. From the attitude of the joints to the axis of causal stress, it is obvious that they were formed at a time when relief was easier upward than laterally (N.-S.). Such a time would be during the second stage of intrusion (third period of joint development), when upward bulging was dominant (Fig. 8).

SYSTEM D.

FOURTH PERIOD OF JOINT DEVELOPMENT

Set 11

Average strike	N. 49° E.
Average dip	55° NW.

The dips of this set of joints grade unbrokenly from 25° to the vertical joints of B-5. They are secondary shear joints that were formed as a result of differential movement between pre-existing joint blocks bounded by joints of B-5. The differential movement was produced by the Laramide orogeny. As the maximum bulge of the local flexure was southeast of Five Springs Creek, the move-

ment between these blocks was up to the southeast; hence, the joints dip to the northwest. Their formation was the same as the formation of fracture cleavage (Fig. 9*a*).

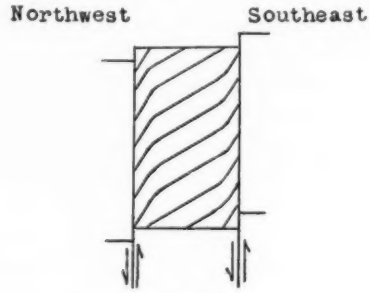


FIG. 9*a*

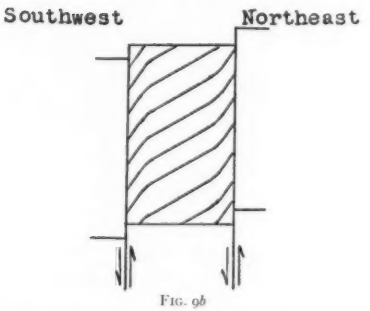


FIG. 9*b*

FIG. 9*a*.—Diagrammatic section showing the mode of origin of System *D*, Set 11, by differential movement between joint blocks bounded by System *B*, Set 5 (N. 45° E.).

FIG. 9*b*.—Diagrammatic section showing the mode of origin of System *D*, Set 12, by differential movement between joint blocks bounded by System *B*, Set 4 (N. 48° W.).

Set 12

Average strike	N. 51° W.
Average dip	57° SW.

These are likewise secondary joints which were produced by differential movement between blocks bounded by joints of B-4. As the strike of B-4 joints roughly parallels the axis of the flexure, the blocks to the northeast would have moved up in relation to the blocks to the southwest and hence the joints dip to the southwest (Fig. 9*b*).

EFFECTS OF CUT-OFF MEANDERS ON THE LONGITUDINAL PROFILES OF RIVERS[1]

PAUL F. MACAR
University of Liége (Belgium)

ABSTRACT

The cut-off of a meander produces a fall or rapid which is later removed upstream by headward erosion. In entrenched valleys, steepened parts of the longitudinal profile may then correspond to cut-off meanders located some miles downstream, and standing now high above the valley bottom. A study of numerous cut-off meanders leads to the conclusion that such steepened parts, having heights corresponding to that of the initial falls do exist really upstream in more than half of the valuable cases. The rate of headward erosion seems affected by the discharge of the stream, being less for small creeks than for more important rivers. In the latter, it equals several hundred times the rate of vertical down-cutting.

INTRODUCTION

The longitudinal profile of a river often presents many irregularities which are usually explained by differences in rock resistance and by rejuvenation (knickpoints).

The purpose of this paper is to draw attention to another possible cause of irregularities in the case of entrenched meandering rivers; namely, the cutting-off of portions of the meandering valley. It is intended to show that those features are responsible for some steepened parts in the profiles of such rivers and, finally, to point out the significance of this fact in regard to headward erosion of falls and rapids.

The cut-off of a meander usually produces a cascade or rapid in the river profile. In rivers flowing on flood plains, the difference in elevation between the two abutting curves at the time of the cut-off is, as a rule, too small to give any conspicuous feature. But some examples are known of falls due to a sudden change in the course of a flooded river and occurring on unconsolidated material, which have

[1] The subject matter of this paper has been presented on several occasions before members of the Seminar in Geomorphology at Columbia University, to whom the writer is indebted for friendly criticisms and suggestions. The study was undertaken at the suggestion of Professor Douglas Johnson, whose helpful advice has been of the greatest value and to whom are due special acknowledgments.

Opportunity for the work was made possible by the Commission for Relief in Belgium Educational Foundation, which appointed the author a Fellow for the academic year 1932–33.

then retreated appreciably upstream in a few days or even in a few hours. Experiments made in the laboratory with a small thread of water flowing on fine sand show likewise a rapid upstream retreat of slight falls artificially produced.

On account of these facts, it seems probable that a fall due to a cut-off in a valley entrenched in hard rocks will likewise retreat upstream but at a much slower rate. In most of the cases the fall will, in the course of time, be reduced to rapids, or even merely to a steeper slope of the river profile. Three closely spaced cut-off meanders, standing now about 150 feet above the river level, have been studied on the Semois in Belgium.[2] A steepened part occurs in the longitudinal profile of that river several miles upstream from the cut-offs. This steepened part is not due to the presence of harder rocks, and its height corresponds to the total fall that should be produced by the cut-offs. The latter seem, therefore, the cause of the steepened part, which has been removed upstream by headward erosion.

The first aim of the present study is to see whether similar relations occur frequently in entrenched meandering rivers of the United States. For this purpose, those quadrangles of the *United States Topographic Atlas* which show cut-off meanders in entrenched valleys have been examined. Quadrangles having more than a 25-foot contour interval have been discarded, for it has been found that the fall produced by a cut-off very rarely exceeds 20 feet; and hence it is believed that its corresponding steepened part, if any, cannot be detected with sufficient accuracy with a 50-foot or larger contour interval. Several small isolated cut-offs have likewise been excluded, their fall being too small (less than 5 feet) to appear on a map with 20-foot contour interval. When two or three of these cut-offs occurred close to each other, however, so that their effect of the river profile might be cumulative, the case has always been studied.

All other mapped cut-off meanders shown on the maps available at the library of Columbia University have been studied, except probably a few which escaped attention and those which failed to be revealed distinctly on the maps or were too doubtful to be taken into consideration. In all, seventy cases were examined and are

[2] P. Macar, "Observations sur des méandres recoupés de la Semois," *Ann. Soc. Géol. Belg.*, T. LV (1931), pp. B. 43–51.

quoted in Table I. To these is added one case (No. 20 of the table) where a small creek emptying into an entrenched meandering river has had its lower course cut off by the lateral migration of a meander of the river. Such a cut-off evidently produced cascades or rapids at the new mouth of the creek and, as far as this study is concerned, has the same effect as a cut-off meander. Finally, the three examples already investigated in Belgium (Nos. 72, 73, and 74) give a total of 74 cases on which conclusions are based.

METHOD OF INVESTIGATION

For each river a longitudinal profile has been constructed by determining the elevation of all points where the different contour lines cross the river, and measuring, along the river channel, the distances between them. Those points, plotted at their proper elevations and distances, represent, as far as permitted by the precision of the maps and of the measurements, real points on the longitudinal profile of the river. But the straight lines which join these points are only approximations of this profile; and the steepened parts thus revealed often extend, in reality, farther downstream or upstream.

Figure 1 shows four possible cases, the real river profile being represented in dotted lines, and the distance *a–b* being the apparent steepened part of each profile as determined by the method employed. It will be observed that the real steepened part is often steeper than the apparent one, and, hence, that small steepened parts, badly located, may not appear at all on the river profile as constructed.

With these limitations in mind, one may proceed to the calculation of the steepened parts which are found in the vicinity of, and upstream from, the cut-off meanders. In doing this, the mean value between the gradients immediately downstream and upstream from the part affected by the steeper slope is taken as a norm, it being assumed that this value represents the normal gradient. The difference between this value and the value of the real gradient in the affected part, multiplied by its length, gives the vertical amplitude of the existing steepened part.

The estimation of the initial fall produced by the cut-off requires measurement of the length of the cut-off part of the river and a

knowledge of the gradient of the river at the time of the cut-off, the product of these two quantities giving the amount of the initial fall. For purposes of this calculation, it is assumed that the river had, at that time, a gradient not very different from the actual one. This assumption seems fair when the cut-off meander stands only a few yards above the actual river level. It may seem less permissible when it stands much higher. In any case, all the measurements made on the map involve some error, since the steepened parts of profiles cannot be determined with great precision. It is believed

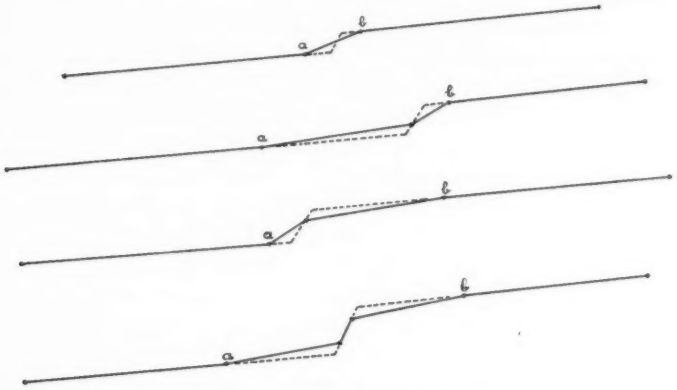


FIG. 1.—Four possible cases where the longitudinal profiles of the rivers, as constructed from the map (in solid lines), do not correspond exactly with the real river profile (in dotted lines). This may lead to a false estimation of the height of the steepened part of profile.

that the assumption stated does not involve a greater error than those due to the map itself.

When it happens that a steepened part of the longitudinal profile is quite close to a cut-off, the gradient chosen for calculation of the initial fall due to the cut-off is that already used for estimation of the existing vertical amplitude of steepened slope. Sometimes a cut-off and a distinct steepened part occur just a little above the mouth of the stream, which empties itself in a more important river. The preceding method is no longer applicable here, because the profile downstream is not normal for the small stream. Whenever another tribu-

tary of about the same importance and flowing on the same rocks occurs in the vicinity, its profile has been assumed to be similar to the normal profile of the stream under investigation, and has been used in the calculations (Nos. 47 and 57 of Table I).

The "age" of a cut-off meander is roughly measured by the height at which it now stands above the river level. In order to have a definite figure to express this height, the vertical distance between the actual river surface and the highest point of the thalweg of the cut-off channel is measured. This figure, which will be called the "height" of the cut-off meander, gives but a rough idea of its age. Since the shortening has occurred, in some cases a little creek or even a more important tributary has eroded and lowered the bottom of the abandoned meander. In other cases there has been, on the contrary, an elevation of the bottom of the abandoned channel, owing to accumulation of material washed from the valley walls and no longer carried away by the river.

INTERPRETATION OF TABLE I

The results of the preceding calculations have been compiled in Table I. This table gives first the indications referring to the location of the cut-off meanders: name of river, quadrangle in which the cut-off occurs, and altitude of the river at the point of cut-off. The last figure permits the identification of the cut-off meander referred to. Data relating to the cut-off meander are then given: these include the "height" of the meander, the amount of shortening, and the fall theoretically produced by it. Wherever a steepened part occurs a few miles upstream, the height of this steepened part is indicated in the table just in front of the figure giving the fall produced by the cut-off, and is followed by the distance measured along the river between point of cut-off and present location of steepened part of profile. As shown in the preceding article, the precise location of the steepened part is often unknown; therefore, the maximum and the minimum possible distances are given whenever they differ notably from each other.

The next column gives, more or less arbitrarily, the size of the river, in an attempt to see whether it has an influence on the rate of retreat of the steepened part of profile. The rivers have been divided

TABLE I

TABLE OF THE CUT-OFF MEANDERS STUDIED WITH THEIR POSSIBLY CORRESPONDING STEEPENED PARTS

Location					Cut-off Meander				Steepened Part		River		Geology	Remarks
Diagram No.	Cut-off No.	River	Quadrangle	State	River Level (Feet)	Height (Feet)	L'gth (Mls.)	Fall (Feet)	Height (Feet)	Distance from Cut-off (Miles)	Size	Flood Plain		
I	1	Wolf R.	Lilydale	Ky.-Tenn.	575	35	2.2	8	.....	.....	Medium	Wide	Variable: siliceous rocks, cherts, and cherty limestones Faint dip upstream	There seems to be a flood plain in cut-off No. 1 The steepened parts cannot be well explained by differences in rock resistance or by rejuvenation
	2	Wolf R.	Byrdstown	Ky.-Tenn.	620	70	2.0	12	.....	.....	Medium	Wide		
	3	Wolf R.	Byrdstown	Ky.-Tenn.	625	45	0.8	5	.....	.....	Medium	Wide		
	4	Wolf R.	Byrdstown	Ky.-Tenn.	630	140	1.3	9		10	Medium	Medium		
	5?	Wolf R.	Byrdstown	Ky.-Tenn.	640	130	0.5	(5)		9	Medium	Medium		
	6?	Wolf R.	Byrdstown	Ky.-Tenn.	650	100	1.0	(9)	32	8	Medium	Medium		
	7	Wolf R.	Byrdstown	Ky.-Tenn.	680	150	0.9	9		5	Medium	Narrow		
	8	Wolf R.	Byrdstown	Ky.-Tenn.	700	95	1.5	15		2.5	Medium	Narrow		
	9	Wolf R.	Byrdstown	Ky.-Tenn.	770	20	0.5	6	6	0– 0.6	Medium	Nearly none		
	10	Spring Cr.	Byrdstown	Ky.-Tenn.	620	110	1.5	25	28	1.5	Small	Medium		
	11	Spring Cr.	Byrdstown	Ky.-Tenn.	760	45	0.3	6	9	0– 0.6	Small	None		
II	12	Fox R.	Elgin	Illinois	710	35	5.0	7	7	0.2– 1.2	Large	Narrow	Nearly horizontal dolomitic limestones	Contour interval 10 feet Glaciated region. Some other steepened parts downstream
III	13?	Kentucky R.	Lockport	Kentucky	445	45	3.0	3?	5?	10	Large	Rather narrow	Nearly horizontal limestones	No other steepened parts than those which correspond to the cut-offs Cut-off meanders Nos. 17 and 18 are much larger and much wider than the others Cut-off No. 13 could be an abandoned meander scarp The steepened part corresponding to cut-offs Nos. 13 and 14 is found only at the mouth of a tributary (Elkhorn Creek) and not on the profile of the Kentucky River itself
	14	Kentucky R.	Lockport	Kentucky	450	35	3.5	3		2	Large	Rather narrow		
	15	Elkhorn Cr.	Lockport	Kentucky	465	65	2.6	20	8	5.2	Medium	Wide		
	16	Elkhorn Cr.	Lockport	Kentucky	495	35	2.0	15	13	6	Medium	Rather wide		
	17	Elkhorn Cr.	Lockport	Kentucky	575	30	4.6	43	9	2	Medium	Rather wide		
	18	Elkhorn Cr.	Franckfort	Kentucky	590	60	4.3	45	13	4.3	Medium	Rather wide		
	19	SouthElkhornCr.	Franckfort	Kentucky	650	25	1.1	10	12	0– 0.25	Medium	Medium		
	20	Cedar Cr.	Lockport	Kentucky	445	60	3.0	<55	>11	0.5	Small	Narrow		
IV	21	Kickapoo R.	Wauzeka	Wisconsin	665	65	3.6	8	.....	.....	Medium	Very wide	Nearly horizontal sandstones with some limestones	The river is strongly misfit, and a little entrenched in its flood plain
	22	Kickapoo R.	Wauzeka	Wisconsin	670	50	3.4	5	.....	.....	Medium	Very wide		

V	23	Brashears Cr.	Taylorsville	Kentucky	470	40	3.4	7–17	6	0– 1	Medium	Very wide	Nearly horizontal limestones	There are other steepened parts upstream, where the stream branches into two tributaries and where it becomes partly intermittent, owing probably to a subterranean course through the limestones
	24?	Brashears Cr.	Taylorsville	Kentucky	490	60	0.8	4	.....	.....	Medium	Narrow		
	25	Brashears Cr.	Taylorsville	Kentucky	605	25	1.3	10	6	0– 0.4	Small	Medium		
VI	26	Potomac R.	Pawpaw	W.Va.-Md.-Penna.	515	155	2.2	5	.....	.....	Large	Narrow	Folded sandstones and shales	Several irregularities due to hard rock ridges or rejuvenation
VII	27	Sleepy Cr.	Hancock	W.Va.-Md.-Penna.	590	25	1.3	10	9	0	Medium	Medium	Folded shales and sandstones	The steepened part forms rapids in the river in front of cut-off
VIII	28	Middle Island Cr.	St. Marys	W.Va.-Ohio	615	75	2.2	2	.....	.....	Medium	None	Nearly horizontal shales and sandstones	Marked steepened part just downstream from cut-off No. 29, and near cut-off No. 28
	29	Middle Island Cr.	West Union.	W.Va.	660	0	3.5	13	12	0	Medium	Narrow		
	30	Middle Island Cr.	West Union	W.Va.	700	50	1.4	4	3	0.3– 4.5	Medium	Narrow		
	31	Middle Island Cr.	West Union	W.Va.	705	30	2.0	6		0– 3.4	Medium	Narrow		
	32	Middle Island Cr.	West Union	W.Va.	740	50	2.0	8	9 & 14	11	Medium	None		
	33?	Buckeye Cr.	Centerpoint	W.Va.	810	40	1.0	6	14	2.5	Small	Narrow		
IX	34	Upper Iowa R.	Decorah	Iowa	900	30	2.3	15	.....	.....	Medium	Narrow	Horizontal limestones and sandstones	Glaciated region
	35	Upper Iowa R.	Decorah	Iowa	925	45	0.9	6	.....	.....	Medium	Narrow		
	36	Upper Iowa R.	Decorah	Iowa	930	20	1.8	12	.....	.....	Medium	Narrow		
X	37	Barren R.	Brownsville	Kentucky	400	25	2.5	2	.....	.....	Large	Medium	Nearly horizontal beds; mostly limestones	Barren River and Drakes Creek have several meanders which do not fit their meander scarps any more; these rivers seem therefore slightly misfit
	38	Barren R.	Bowling Green	Kentucky	410	50	2.5	4	.....	.....	Large	Medium		
	39	Barren R.	Scottsville	Kentucky	475	35	4.0	5	14	4– 8	Large	Wide		
	40	Barren R.	Scottsville	Kentucky	520	30	2.5	5	6	0– 6	Medium	Wide		
	41	Drakes Cr.	Bowling Green	Kentucky	430	20	2.1	4	.....	.....	Medium	Wide		
	42	Drakes Cr.	Bowling Green	Kentucky	435	15	1.8	3	.....	.....	Medium	Wide		
	43	Drakes Cr.	Bowling Green	Kentucky	455	15	1.0	2	.....	.....	Medium	Medium		
	44	Drakes Cr., West Fork	Bowling Green	Kentucky	470	25	1.5	4	.....	.....	Medium	Narrow		
	45	Long Cr.	La Fayette	Kentucky	555	0	1.3	9	.....	.....	Small	Wide		
XI	46	Auxvasse Cr.	Fulton	Mo.	545	45	1.0	5	6	4.4	Medium	Wide	Nearly horizontal beds; mostly limestones	Glaciated region. River slightly misfit downstream from cut-off No. 46
	47	Auxvasse Cr.	Fulton	Mo.	550	40	0.8	4		3	Medium	Wide		
	48	Auxvasse Cr.	Fulton	Mo.	605	25	1.4	9	3	0– 1.6	Medium	Narrow		
XII	49	Dry Fork	Meramec Spring	Mo.	830	40	2.4	11	13? 20?	19 5	Medium	Medium	Horizontal beds; mostly limestones	The second steepened part occurs on a tributary. Both steepened parts are very far from the cut-offs

TABLE I—*Continued*

Location					Cut-off Meander				Steepened Part		River		Geology	Remarks
Diagram No.	Cut-off No.	River	Quadrangle	State	River Level (Feet)	Height (Feet)	L'gth (Mls.)	Fall (Feet)	Height (Feet)	Distance from Cut-off (Miles)	Size	Flood Plain		
XIII	50	Wolf R.	Caldwell	Ohio	640	45	2.5	13	10	0– 0.3	Small	Narrow	Nearly horizontal shales and sandstones	
XIV	51	Fishing Cr.	Littleton	W.Va.-Pa.	675	35	1.2	4	.....	.....	Medium	Narrow	Nearly horizontal shales, sandstones, and limestones	Marked steepened parts downstream from the cut-offs
	52	Fishing Cr., South Fork	Littleton	W.Va.-Pa.	740	65	1.2	13	10	3	Small	Narrow		
	53	Sunfish Cr.	Clarington	Ohio-W.Va.	640	70	1.4	11	7	3	Medium	Narrow		
	54	Fish Cr.	Cameron	Ohio-W.Va.-Penna.	705	140	1.4	8		2.5– 6.5	Medium	Narrow		
	55	Fish Cr.	Cameron	Ohio-W.Va.-Penna.	715	35	0.8	5	18	0.8– 4.8	Medium	None		
	56?	Fish Cr.	Cameron	Ohio-W.Va.-Penna.	740	70	1.7	10		0 – 2	Medium	Narrow		
XV	57	Big Cr.	Chardon	Ohio	610	10	0.5	8	12	0 – 0.3	Small	Medium	Nearly horizontal shales	Glaciated region. Other steepened parts at the mouth of Paine Creek
	58	Paine Cr.	Chardon	Ohio	645	45	0.8	11	36–8	1 – 2.3	Small	Medium		
	59	Paine Cr.	Chardon	Ohio	660	110	0.4	16		0 – 1.2	Small	Narrow		
XVI	60	Yellow Cr.	Wellsville	Ohio-W.Va.-Penna.	740	70	1.7	11	17	3 – 5	Medium	None	Nearly horizontal shales and sandstones	Raccoon Creek is slightly misfit upstream from the cut-off
	61	Yellow Cr.	Salineville	Ohio	800	50	1.0	7	.....	.....	Medium	Medium		
	62	Yellow Cr.	Salineville	Ohio	815	35	1.4	9	.....	.....	Medium	Narrow		
	63	Raccoon Cr.	Beaver	Penna.	765	25	1.5	10	5	2 – 4	Medium	Wide		
XVII	64	Dan R.	Stuart	Va.-N.C.	1,040	55	1.2	22	17	3 – 5	Medium	Narrow	Folded crystalline beds	
	65?	Dan R.	Stuart	Va.-N.C.	1,100	90	1.0	20	.....	.....	Medium	Medium		
XVIII	66	Mahoning Cr.	Rural Valley	Penna.	865	85	2.2	10	7–20	8	Medium	Narrow	Slightly folded sandstones and shales	Two tributaries occur upstream from cut-off No. 67, but only one of them shows a steepened part
	67	Mahoning Cr.	Smicksburg	Penna.	1,110	100	1.7	9	12	2.5– 4.5	Medium	Medium		
									.....	.....				
XIX	68	Nolin R.	Cub Run	Kentucky	480	110	1.5	3	18	9	Medium	None	Slightly folded sandstones and limestones Fault at the steepened part Nos. 68–69	The steepened part No. 68-69 may be related, directly or indirectly, to the fault occurring there. The steepened part No. 71 has been described* as corresponding to the cut-off. It extends over 400 feet
	69	Nolin R.	Cub Run	Kentucky	495	35	2.0	4		4	Medium	None		
	70	Nolin R.	Cub Run	Kentucky	535	35	2.8	3	.....	.....	Medium	None		
	71	Dog Cr.	Cub Run	Kentucky	475	15	1.7	9	27	0 – 0.1	Small	None		
XX	72	Semois R.	Orchimont	Belgium	585	215	2.0	31	30	15	Large	Narrow	Folded slates and shales	Study in the field has shown that the steepened part is not due to the occurrence of harder layers
	73	Semois R.	Orchimont	Belgium	590	140	2			13.5	Large	Narrow		
	74	Semois R.	Orchimont	Belgium	595	165	1.5			11	Large	Narrow		

* Ellison, *Pan. Amer. Geol.*, Vol. L (1928), pp. 5–6.

into three groups, defined by the adjectives "small," "medium," and "large." By "small" rivers, it is intended to designate the little creeks, a few miles long, which are usually represented by a single blue line on the map. The term "large" applies, for instance, to streams of the size of the Potomac and Kentucky rivers in their middle courses; whereas under the term "medium" are gathered a great many streams of lesser volume, but always represented by more than one single line on the maps studied.

The width of the flood plain, if any, is mentioned next, the flood plain being described as "very wide" when the river has reached full maturity. In this latter case, the fall due to a cut-off has much less chance of being preserved, because the river is more likely to flow on unconsolidated deposits. The fall will then occur, at least partly, on those deposits, and will soon be entirely removed or will retreat so far that it can no longer be detected.

A very brief account of the geology of the region is given in the next to the last column. The data on the nature and the structure of the rocks have been taken, in most of the cases, from the geological maps of the states, or whenever possible, from the United States Geological Survey folios. The remarks in the last column give information about special features: they indicate whether the region has been glaciated; if there are, on the river profile, other marked steepened parts than those mentioned in the table; etc.

In some cases it has not been possible, from examination of the map, to decide definitely whether one had to deal with a true cut-off meander, with an abandoned meander scarp, or some quite different feature. Those doubtful cases, which are excluded from the final discussion, have been cited and studied, because whether or not one considers them as true cut-off meanders is largely a matter of personal opinion. It seemed desirable to record all facts which might have possible pertinence.

RESULTS FURNISHED BY TABLE I

None of the steepened parts indicated in Table I are found in connection with known hard-rock layers represented on the geological maps. It is possible, nevertheless, that some may coincide with hard layers too small to be shown on the map. This would not prove

however, that the steepened parts of such profiles are due directly to the presence of these beds, since resistant rocks will, in any case, arrest or retard the headward retreat of steepened parts due to whatever cause.

It is not often possible to tell from the mere examination of the map whether or not a steepened part apparently due to a cut-off meander is susceptible of some other alternative explanation. Table I is presented as offering merely statistical evidence. If, out of many examined cut-off meanders, there is a sufficient number of cases in which steepened parts of appropriate heights do occur a short distance upstream from the cut-offs, there is a good reason to believe that a correlation exists between the two features. It is quite possible in some cases, that the apparent correspondence is only due to chance. But, on the other hand, some really significant steepened parts may not be revealed on the profiles because of unavoidable inaccuracy in measurements. There should be some rough compensation between these two opposed possibilities of errors.

To discuss the significance of the table, the term "corresponding steepened part" has now to be defined in terms of definite figures. This involves an element of personal judgment. The calculated falls due to cut-off meanders and the neighboring steepened parts are here regarded as "corresponding" whenever their heights differ by 5 feet or less. This arbitrary limit has been chosen because the total possible error due to the calculations easily reaches this value and probably exceeds it in many cases.

Table I gives the data relative to 74 cut-off meanders. These are divided, in Table II, into different sections:

1. The isolated cut-offs producing a fall 5 feet or less in height which have to be excluded, because their corresponding steepened parts of profiles are too small to be detected or because small irregularities, caused, perhaps, by inaccuracy of measurements, could easily be mistaken for steepened parts genetically associated with the cut-offs.

2. Doubtful cases; apparent but not certain cut-offs; steepened parts impossible to calculate accurately enough because of their location; etc.

3. A few cases of quite recent cut-offs, where the corresponding steepened part is still at the point of cut-off.

TABLE II

DISTRIBUTION OF THE CUT-OFF MEANDERS ACCORDING TO EXISTENCE, HEIGHT, AND LOCATION OF THEIR POSSIBLY CORRESPONDING STEEPENED PARTS

Cut-off Producing Falls of 5 Feet or Less	Doubtful Cases	Recent Cut-offs	Cut-offs on Misfit Rivers	Cut-offs with Steepened Parts			
				Possibly Not Upstream	Removed Upstream	Not Corresponding to Calculated Original Fall	Not Evident
Case No.							
3	5*	27	21	9	4	15	1
13	6	29	22	11	7	17	2
14	20*	45		19	8	18	34
24	23*			25	10	30	35
26	33			50	12	31	36
28	49			57	16	48	61
37	56*				32	60	62
38	58*				46	68	
39	59*				47	69	
40	65				52		
41	66*				53		
42	67				54		
43	71*				55		
44					63		
51					64		
70					72		
					73		
					74		
Totals							
16	13	3	2	6	18	9	7
34				40			

* *Probable cut-off meander* with corresponding steepened part or true cut-off meander with *probable* corresponding steepened part.

4. Two cut-off meanders occurring on a notable misfit river. Here changes in conditions, including probable aggradation of the river, have most likely obliterated effects of the cut-offs, which occurred before the stream acquired its misfit character.

All these cases have been excluded from the final discussion. It should be noted, however, that about half of the doubtful cases (those which are marked by an asterisk [*] in the table) are either *probable cut-off meanders* with corresponding steepened parts or true cut-offs with *probable* corresponding steepened parts. The elimination of the preceding cases, 34 in number, leaves 40 cut-offs for final discussion. Those are likewise divided into four groups (Table II):

5. Six of them, rather recent, have a corresponding steepened part of profile, but the river profile is not precise enough to determine whether this is still at the point of cut-off or has already been removed a small distance upstream.

6. Eighteen cut-offs have been found with corresponding steepened parts of profile distinctly removed upstream. The maximum removal—15 miles—was found in Belgium (No. 72), for a cut-off meander standing 215 feet above the river level.

7. In nine other cases there is a steepened part of the profile a few miles upstream from the cut-off, but its height does not correspond to the fall theoretically produced by the latter.

8. Finally, seven cut-off meanders have been found without any upstream steepened part of profile evident on the maps examined.

It will be observed that 16 cases out of 40 do not show the theoretically ideal relation; 18 cases do show it surely; and the 6 remaining cases may or may not show it. A correspondence between cut-offs and steepened parts of profiles is found in about 55 per cent of the cases. This percentage seems to the writer much too high to be due to chance.

The lack of a steepened part, or the presence of only a too small one, may sometime be due to the fact that the fall produced by the cut-off occurred entirely or partly on alluvium, as already suggested. One may suppose, too, that the steepened part is reduced in height with time. There are more cases, however, 16 at least—where this height is not apparently diminished.

A steepened part exceeding the calculated original height of the fall due to cut-off may be due to the presence of harder rocks, which have checked the upstream retreat of the fall and have added to it a steep slope resulting solely from failure of the stream to grade its

course in the resistant rocks. It is not surprising that the expected correspondence does not appear in all cases, because every river profile shows many little irregularities, most of them as yet unexplained, which may veil a correlation that would otherwise be evident.

It was hoped, when beginning this study, that some relation would be found between the rate of upstream removal and either the discharge of the river or the nature of the bedrock. Unfortunately, these factors cannot be determined with sufficient accuracy, and the favorable cases are not numerous enough to afford reliable conclusions.

There is, however, some indication that the discharge of the river is an important factor; for cut-off meanders standing at about the same height above the river level, the upstream removal appears notably smaller in little creeks than in large rivers. This fact is emphasized by Table III, which gives for diverse cases divided into small, medium, and large rivers the amount of relative upstream removal, i.e., the distance of removal corresponding to 1 foot of down-cutting. This figure is obtained by dividing, in each case, the measured distance of removal (expressed in feet) by the "height" of the cut-off meander. It has already been pointed out that the latter was only to be considered as a rough approximation.

The mean value for the little creeks is decidedly smaller than for the greater rivers. Table III suggests that the rate of headward erosion is about 50 times greater than the rate of down-cutting for the former, and about 350 times for the latter. But these figures ought to be taken only as a vague indication, for the individual figures vary greatly, and the mean value for the large rivers is even slightly smaller than that for the medium-sized streams. The number of cases is insufficiently large. The term "medium-sized" is applied to rivers having discharges of very different magnitude, and the varying nature and structure of the bedrock undoubtedly have some disturbing effect.

Vague as they are, these figures are nevertheless interesting. They show the preponderance of headward erosion over vertical down-cutting, a preponderance amounting to several hundred fold in medium-sized and large rivers. This favors strongly the idea already ex-

pressed by some authors that the downward erosion of a river is due much more to the upstream retreat of small steepened parts than to a general scouring all along the river course.

TABLE III

DISTANCES OF UPSTREAM REMOVAL OF THE STEEPENED PART CORRESPONDING TO 7 FEET OF DOWN-CUTTING

MEDIUM-SIZED RIVERS			SMALL CREEKS		
Case No.	Relative Removal (Feet)	Rocks	Case No.	Relative Removal (Feet)	Rocks
4	380	Variable	10	70	Variable
7	180	Variable	11	0–70	Variable
8	140	Variable	25	0–80	Limestones
16	900	Limestones	50	0–40	Shales and sandstones
32	1,160	Shales and sandstones	57	0–160	Shales
46	520	Limestones			
47	400	Limestones	Mean	50	
52	240	Variable			
53	230	Variable			
54	90–250	Variable	LARGE RIVERS		
55	120–720	Variable			
63	420–840	Shales and sandstones	Case No.	Relative Removal (Feet)	Rocks
64	110	Crystalline beds			
9	0–160	Variable			
19	0–50	Limestones	12	30–180	Limestones
			72	370	Slates
			73	510	Slates
			74	350	Slates
Mean	370		Mean	360	

CONCLUSION

The cut-off of a meander in an entrenched meandering river produces a fall or rapid which is later removed upstream by headward erosion.

This feature, reduced to a steepened part of the profile, can still be detected in many cases.

The rate of headward removal seems notably less for small creeks than for more important rivers. In the latter, it is several hundred times greater than the rate of vertical down-cutting.

THE ASYMMETRY OF THE "*PEPINO* HILLS" OF PUERTO RICO IN RELATION TO THE TRADE WINDS

JAMES THORP[1]
U.S. Dept. of Agriculture, Bureau of Chemistry and Soils,
Washington, D.C.

ABSTRACT

The Tertiary limestones in the coastal plain of northern Puerto Rico are characteristically eroded into rugged conical hills, which usually possess a distinctively asymmetric cross section. The asymmetry is systematically oriented with respect to the trade winds, and its origin appears to be due in large part to differential solution promoted by wind-borne rains.

Practically every newcomer to Puerto Rico who travels from San Juan to Arecibo is profoundly impressed by the peculiar "haystack" or "*pepino*" (cucumber) hills which occur between these two cities and elsewhere in the northern Tertiary limestone belt. These hills are derived from various horizons of the Tertiary limestones, which form a belted coastal plain several miles in width along the northern coast of the island. Most of the hills of this type which are encountered on the main highway occur individually or in small groups, protruding from flat or mildly undulating country. They are relatively small in area, steep-sided, and abrupt, ranging in height from 25 to 300 feet. Careful observation in the field, or an examination of aerial photographs, shows that the hills are arranged in fairly regular east-west bands. In some places there may be only a few to the square mile, with large intervening spaces of open undulating plains. Farther inland in the lower horizons of the Quebradillas and Lares limestones (two of the formational subdivisions of the Tertiary) the *pepino* hills occupy most of the area and are separated only by deep sinkholes and narrow solution valleys. The hills themselves are extremely cavernous.

The hills owe their origin primarily to differential solution. Practically all of the runoff of meteoric waters is accomplished through

[1] The author is indebted to Howard A. Meyerhoff for reading the manuscript and giving valuable constructive criticisms which have been embodied in the text.

underground channels. The roofs of caves thus formed have fallen in thousands of places, and limestone has been dissolved from the surface in tremendous quantities, with the result that only the more resistant parts have been left standing as *pepino* residuals. Hubbard[2] and Meyerhoff[3] have described these hills at considerable length, and the reader is referred to their works for further details.

While the author was making a soil survey of the region south and west of Arecibo, he noted that the limestone hills, when viewed from the southeast or northwest, exhibited a peculiar saw-tooth profile, with the points of the saw-teeth practically always oriented southwest or west-southwest.[4] They give the appearance of having been warped out of shape by the prevailing trade winds which, in this region, blow almost continually from the east-northeast. Trees which grow in exposed positions in open valleys or on exposed ridges are characteristically deformed by the wind. The limbs on the windward side are short, deformed, and curled back, whereas those on the lee side are long and luxuriant. It is possible in many places to observe a tree deformed in this manner, and beyond it a limestone hill with a somewhat similar profile.[5]

The hills situated on the more open plains usually have relatively gentle slopes on their windward sides, which rise from the general level of the plains. The angle varies from a few degrees to as high as 45°. From the crest of each hill the leeward slope drops off very

[2] Bela Hubbard, *The Geology of the Lares District, Porto Rico* (N.Y. Acad Sci., Sci. Surv. of Porto Rico and the Virgin Islands, Vol. II, Part 1, 1923), pp. 83–93.

[3] H. A. Meyerhoff, *The Geology of the Fajardo District, Porto Rico* (N.Y. Acad. Sci., Sci. Surv. of Porto Rico and the Virgin Islands, Vol. II, Part 3, 1931), pp. 327–30; The Geology of Puerto Rico. *Univ. Puerto Rico Mono.*, Ser. B, No. 1 (In press), pp. 168–72.

[4] The features of asymmetry were called to the attention of several scientists, and the author's observations were amply confirmed. L. R. Smith, J. Landrón, and D. Rodríguez, all of whom were assisting in the soil survey of Arecibo, and Dr. N. L. Britton of the New York Botanical Garden and Dr. H. A. Meyerhoff of Smith College offered abundant supplementary material. To these the author expresses his appreciation.

[5] Figure 1 (*a*) illustrates the phenomenon clearly. Figure 2 is a map of the locality from which the photograph in Figure 1 (*a*) was taken. Arrows indicate the direction of the trade winds: *A* is the hill which is shown in the photograph and *B* shows the position of the camera. The map was made from an aerial photograph and, although the contours indicate positions of equal altitude on each hill, no attempt was made to measure the exact elevations. It may be readily seen from this map that the summits of practically all of the hills are located west or southwest of the center.

rapidly, with overhanging cliffs characterizing many of them. Sinkholes occur without apparent discrimination on any side of the hills, hence the asymmetry seems unrelated to the subsurface solution.

Fig. 1. (*a*)—Asymmetrical limestone hill in the Tertiary coastal plain of northern Puerto Rico. Note parallel deformation in both tree and hill. View toward south-southeast.

Fig. 1. (*b*)—A group of serrate *pepino* hills in the Quebradillas formation, as seen from the south-southeast, near Barceloneta.

In the areas where the *pepino* hills are closely crowded, they may rise vertically on all sides from narrow sinkhole valleys to elevations of 200 feet or more. If, however, the top of any hill rises to a sufficient height to reach the sweep of the trade winds, its summit is al-

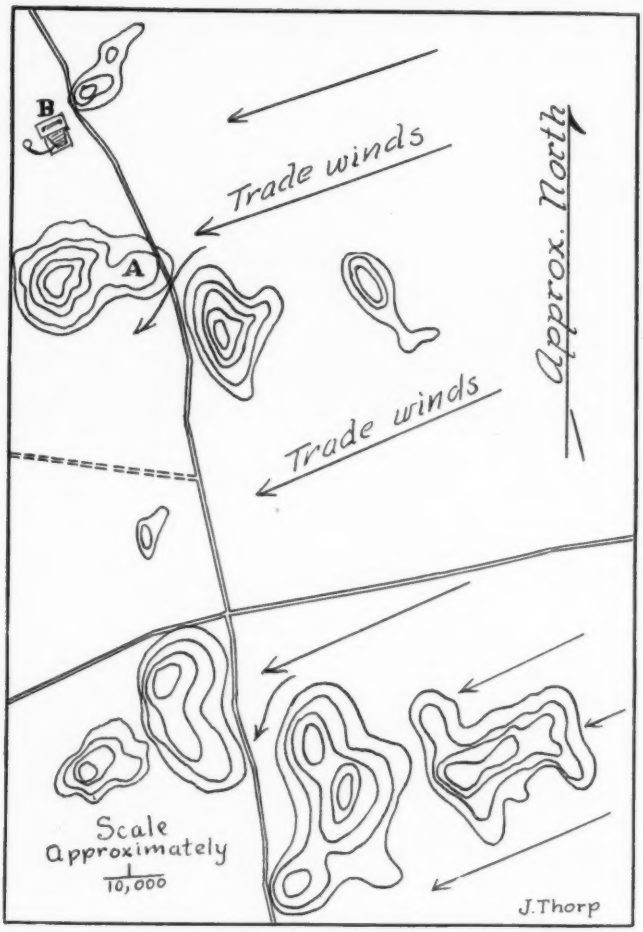


FIG. 2.—Map of limestone hills about 8 kilometers southeast of Hatillo. *A* is the hill shown in Figure 1 (*a*). *B* is the position from which the photograph was made. Contour lines show shape of hills but altitudes were not determined. Map made from aerial photograph.

most invariably shaped into the characteristic saw-tooth form. Thousands of such hills were observed. It was noted, however, that many smaller *pepinos* in the crowded belts are so low that they fail to lift their summits high enough to intercept the trade winds. Other higher hills to windward cut off the air currents and leave them in a position of relative calm. These protected hills show no signs of systematic deformity and are haphazardly irregular in shape. Hundreds of such hills may be seen in the Quebradillas limestone outcrops between the Guajataca Reservoir and the Arecibo-Lares road. More specifically, several were noted on the east side of the Río Camuy canyon.

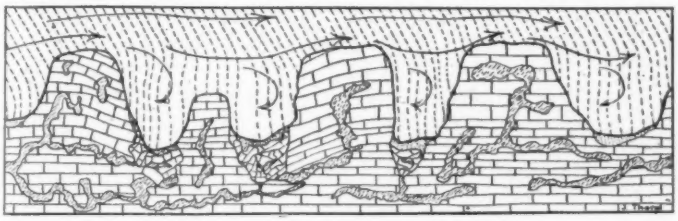


FIG. 3.—Generalized section showing assumed original shape of limestone hills and sinkhole valleys before differential solution. Shaded areas are caverns in the limestone. Arrows show direction of trade winds and parallel dashed lines show approximate course of falling rain. East-northeast to west-southwest from left to right.

A review of the literature on the northern Tertiary coastal plain of Puerto Rico indicates that Hubbard[6] was the only geologist who noticed the saw-tooth shape of the limestone hills. He described the steep western slopes of the hills, but apparently he did not note the relationship between their direction and that of the trade winds. In common with the writer, Hubbard found that the saw-tooth shape of the hills had no relation to slumping, tilting, dip, structure, or composition of the rock (Figs. 3 and 4), and he likewise concluded that their shape was due to differential solution. It is difficult, however, to accept his explanation of how differential solution takes place. His theory utilizes the fact that the almost daily showers occur in the afternoon when, presumably, the western slopes have been heated to

[6] *Op. cit.*, p. 92.

a higher temperature than the shaded eastern slopes. He assumed that there would, in consequence, be more rapid evaporation on the western slopes, hence more water would be free to act as a solvent on the eastern slopes.

Hubbard's theory is open to several objections. In the first place, inasmuch as the northern slopes receive direct sunlight for only a short period each year, they would be, on the average, cooler and moister than the other slopes and, in accordance with the theory, one would expect the warm south slopes to become steep through the evaporation of water, and the northern sides to be dissolved into long gentle slopes. This is not the case.

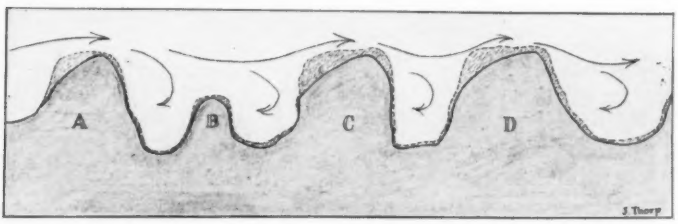


FIG. 4.—Generalized section showing the effect of long exposure of hills in Figure 2 to wind-blown rain. Shaded area represents new shape of hills, and hachured area shows material which has been dissolved away.

In the second place, rains that furnish enough water to produce any great effect must be of sufficient volume to soak through the thin surface soil and rock, and either run off in rivulets or, more commonly, penetrate to underground channels. Water has a very high specific heat in comparison with soil and rock, and a large volume of water would have so great a cooling effect on the soil and rock as to neutralize the effect of differences in temperature between the shady and sunny sides. Furthermore, the original forest cover of the hills, which may still be seen in a few localities, was so dense that its shade would largely offset the effect of the differences in temperature between the eastern and western slopes. Probably the greatest amount of rock solution occurs during rainy periods which may last for two or three days, or for two or three weeks at various times of year. During these periods the sun has very little effect as a differential heating agent.

Finally, Hubbard's theory will not fit the case of the low, irregularly shaped *pepinos* which are situated on the lee sides of large hills, and which lack the asymmetry characteristic of those exposed to the trade winds. Although these small hills are protected on the windward side by higher hills, the early afternoon sun is nearly always able to reach them and warm their western and southwestern flanks. If the theory is valid, these hills should be deformed like their higher neighbors, except where their formation has been of too recent a date.

The author believes that the following explanation will account fully for the saw-tooth shape of the limestone hills of northern Puerto Rico. Although the processes involved were doubtless acting concurrently, they will be discussed separately. After the deposition of the Tertiary limestones and their subsequent emergence from the sea, they were leveled by erosion to a relatively flat peneplain. When this plain was later elevated, the streams were rejuvenated and a new cycle of erosion began. The harder and purer limestones were honeycombed by myriads of caves, through which underground streams carried off practically all of the waters that fell at the surface. As solution proceeded, a great series of sinkholes was formed. At the same time solution of rock near the surface had been forming pockets and small valleys in the less resistant of the limestones. The ultimate result was the formation of a series of steep-sided hills and valleys, much as is shown in Figure 3. These were irregular in shape. Locally the beds were tilted by slumping of the rocks into subterranean caverns, but in most places they remained essentially in their original positions.

While the hills and valleys were forming, and after they were formed, the trade winds were blowing more or less continually over the lands. Showers were frequent, and heavy rainstorms quite common. Rain falling in a still atmosphere will, of course, fall in a perpendicular line, and all flat surfaces will become equally wet. If there are cliffs or steep slopes, the flattest areas will receive the most rain per unit surface. Under such conditions any steep hill made of homogeneous material will be rounded off more or less equally on all sides.

In the case under consideration, however, the rain clouds are mov-

ing with the trade winds toward the west-southwest, and the rain is being blown in the same direction. The resultant of the force of gravity and the force of the wind imparts to the raindrops a diagonal course in their downward movement. Assuming an equal spacing of raindrops, a much larger amount of water per unit of surface will fall on the tops of the hills and on the windward slopes than will fall on the lee slopes (Fig. 3). This one factor alone would be sufficient to account for the migration of the hill summits toward the west-southwest, for processes of chemical and mechanical erosion would both be accelerated, and both would co-operate in smoothing and lowering the windward slopes at a comparatively rapid rate. Figure 4 gives a generalized idea of the results of such a process. The small hill in Figures 3 and 4 is protected from the trade winds, and the rain tends to fall on it vertically, giving it a more or less symmetrical shape. If the process continues long enough, the large hills will gradually be reduced until the small hill will be exposed to wind-blown rain; then it will become asymmetrical like the others. This will take place, of course, only if the small hill is eroded less rapidly than its higher neighbors.

The question has been raised as to whether the hard Cretaceous limestones in the interior of the island exhibit a corresponding asymmetry. It has also been suggested that hills of non-calcareous volcanic and sedimentary rocks might develop an erosional profile similar to that of the "*pepino* hills" as a result of mechanical erosion. The more exposed Cretaceous limestone hills near San German do show an asymmetry just like that of the *pepino* hills of northern Puerto Rico. Other outcrops of Cretaceous limestone observed by the author, with this phenomenon in mind, were in positions not sufficiently exposed to the trade winds to be noticeably affected. A careful study of these limestones may very possibly bring new cases to light. No study has been made of the non-calcareous "oldland" hills to determine whether such reshaping is in progress among them. Many places casually observed seem to offer evidence of this type of erosion, but it would require careful study to check all of the factors involved. This is a problem for future investigation.

Limestone hills similar to those in northern Puerto Rico are known to exist in other islands of the West Indies. In fact, the development

of *pepino* topography is characteristic of limestones in humid tropical countries. Presumably, wherever limestone hills like these occur in the trade-wind belt, a similar asymmetry should be found, if the proposed theory is correct.

SUMMARY

Puerto Rico's limestone or "*pepino*" hills are largely the products of differential solution. They are characterized by their asymmetric saw-tooth cross section, with the gentle slope of each hill facing toward the east-northeast into the trade winds. Hubbard,[7] who observed and described the phenomenon, did not associate it with the trade winds, but ascribed it to differential solution brought about by the difference in temperature between the eastern and western slopes. According to his theory, the rain from the almost daily showers, which usually occur after noon when the sun has warmed the western slopes, is more rapidly evaporated on the western than on the eastern hillsides. Hence more rock is dissolved from the east than from the west. There is, however, more reason to believe that the strong northeasterly trade winds, which necessarily drive more water against the windward sides of the hills, are causing more rapid solution and mechanical wear of the windward slopes than of the leeward slopes, and that this simple explanation may fully account for the phenomenon.

[7] *Ibid.*, pp. 92–93.

A CONTRIBUTION TO ANTARCTIC PETROGRAPHY[1]

DUNCAN STEWART, JR.
Carleton College

ABSTRACT

A quantitative study is made of the composition of various pre-Cambrian igneous and metamorphic rocks from Marie Byrd and King Edward VII Lands, Antarctica.

THE MARIE BYRD LAND SCHISTS

The Queen Maud Mountains extend from Beardmore Glacier, South Victoria Land, in approximately latitude 84° S., longitude 172° E., eastward into Marie Byrd Land to at least longitude 140° W., and form the southern boundary of the Ross Shelf ice.[2] These block-fault mountains, in South Victoria Land, are composed of a thick series of sedimentary rocks with diabase sills, known as the Beacon sandstone[3] which ranges from Upper Devonian to possibly Triassic age, and which rests upon a pre-Cambrian basement of igneous and metamorphic rocks. Dr. Laurence M. Gould, geologist of the Byrd Antarctic Expedition, 1928–30, collected seven rocks, ranging from biotite to biotite-hornblende schists from Supporting Party Mountain in the Queen Maud Mountains of Marie Byrd Land (Fig. 1). These specimens are the first to be examined from this region and came from the pre-Cambrian basement rocks.

[1] The writer wishes to thank Dr. Laurence M. Gould for the opportunity of examining these specimens, and Dr. William H. Hobbs and Dr. Walter F. Hunt who gave much valuable advice and aid in the laboratory. Professor A. Lacroix was very generous in supplying the author with 16 duplicate rock specimens for comparative purposes collected by the Expédition Antarctique Française, 1903–5, in the Antarctic Archipelago.

[2] L. M. Gould, "Some Geographical Results of the Byrd Antarctic Expedition," *Geogr. Rev.*, Vol. XXI, No. 2 (1931), pp. 177–200; "Structural Relationships of the Queen Maud Mountains, Antarctica," *Proc. Geol. Soc. Amer., Abs.* (1934).

[3] Duncan Stewart, "The Petrography of the Beacon Sandstone of South Victoria Land," *Amer. Mineral.*, in press.

PETROGRAPHY

The collection includes the following rock types: hornblende-biotite, orthoclase-biotite, biotite-orthoclase, and biotite schists. A chemical analysis of a biotite schist, 31*e*, has been recorded.[4] Table I

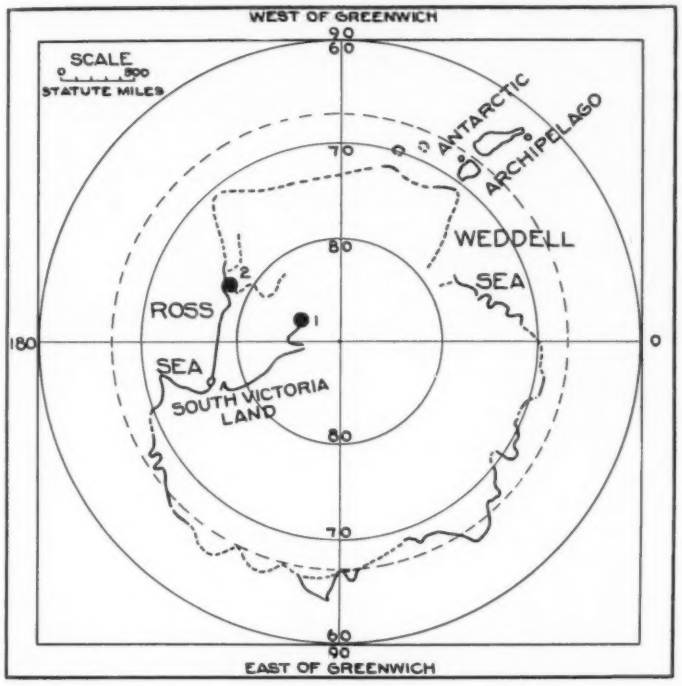


FIG. 1.—Sketch map of Antarctica. (1) Supporting Party Mountain, Queen Maud Mountains, Marie Byrd Land; (2) Rockefeller Mountains, King Edward VII Land.

gives the minerals and quantitative measurements of the constituents of eleven thin sections, the latter determined with the improved Wentworth recording micrometer.[5]

[4] *Ibid.*

[5] W. F. Hunt, "An Improved Wentworth Recording Micrometer," *Amer. Mineral.*, Vol. IX, No. 9 (1924), pp. 190–93.

TABLE I

MINERALOGICAL COMPOSITION OF THE SCHISTS FROM SUPPORTING PARTY MOUNTAIN, QUEEN MAUD MOUNTAINS, MARIE BYRD LAND

MINERAL	SPECIMEN										
	31*a*	31*b**	31*b*†	31*c**	31*c*†	31*d**	31*d*†	31*e**	31*e*†	31*f*/*x**	31*f*/*x*†
Quartz	43.65	21.03	21.81	29.52	36.02	47.27	58.10	50.09	50.13	64.31	63.96
Microcline	18.10	45.14	41.25	29.61	34.13						
Orthoclase						0.82	0.15	0.76	2.17	2.57	7.97
Plagioclase	3.69	0.63	0.42	1.58	0.58						
Biotite	10.15	32.19	35.37	38.15	25.82	43.60	27.71	46.55	37.13	31.02	25.47
Chlorite	*p*	*p*	*p*	*p*	*p*	*p*	*p*			*p*	*p*
Green hornblende	23.26										
Augite											
Titanite	0.58	*p*	*p*							*p*	*p*
Muscovite						4.14	9.42	1.21	8.98	1.58	1.82
Calcite	0.58	0.49	0.55	1.15	2.54					0.52	0.78
Apatite								*p*	*p*		
Zircon		*p*	*p*					*p*	*p*		
Garnet						4.18	4.63	1.30	1.22		
Tourmaline										*p*	*p*
Sillimanite											
Rutile		*p*	*p*							*p*	*p*
Clinozoisite		0.49	0.45								
Epidote				*p*	*p*					*p*	*p*
Magnetite		0.02	0.15			*p*	*p*		0.37	*p*	*p*
Ilmenite	*p*			*p*	*p*					*p*	*p*
	100.01	99.99	100.00	100.01	99.99	100.01	100.01	100.00	100.00	100.00	100.00

* Section parallel to schistosity.

† Section perpendicular to schistosity.

p = present in thin section.

31*a*. Hornblende-biotite schist
31*b*. Orthoclase-biotite schist
31*c*. Biotite-orthoclase schist
31*d*. Biotite schist
31*e*. Biotite schist
31*f*/*x*. Biotite schist

ACID INTRUSIVE ROCKS OF ROCKEFELLER MOUNTAINS, KING EDWARD VII LAND

Late in the year of 1911, Prestrud, a member of Roald Amundsen's South Pole Expedition,[6] led a sledging party into King Edward VII Land. Prestrud collected specimens of acid intrusive rocks, gneisses, and amphibolite at Scott's Nunatak, north of the Rockefeller Mountains, which have been described by Schetelig.[7] Gould,[8] in March of 1929, made a geological reconnaissance of the low-lying peaks and ridges of the Rockefeller Mountains. These mountains

[6] Roald Amundsen, *The South Pole* (2 vols.), *The Eastern Sledge Journey by K. Prestrud*, Vol. II (London: John Murray, 1912), pp. 204–79.

[7] J. Schetelig, "Report on the Rock Specimens Collected on Roald Amundsen's South Pole Expedition," *Videnskapsselskapets Skrifter I, Mat.-naturv. Klasse*, No. 4 (Christiania, 1915), pp. 1–31.

[8] *Op. cit.*, pp. 177–80.

are composed of monzogranite intruded by coarsely crystalline acid dikes, and cut by veins of quartz.

PETROGRAPHY

The following are the rock types in the collection from the Rockefeller Mountains: monzogranite,[9] alaskite, porphyritic leucomonzo-

TABLE II

MINERALOGICAL COMPOSITION OF THE ROCKS FROM THE ROCKEFELLER MOUNTAINS OF KING EDWARD VII LAND

MINERAL	SPECIMEN					
	1br	2r	3br	4r	5r	6r
Quartz	34.42	32.49	35.37	*p*	58.43	37.67
Orthoclase	47.81	53.82	48.63		27.13	38.87
Microperthite						
Albite		7.32		*p*		
Albite-oligoclase	11.68		12.66		11.62	18.55
Biotite	5.48			*p*		4.87
Magnetite		4.06	3.03		1.59	
Chlorite				*p*		
Muscovite						*p*
Zircon				*p*		*p*
Fluorite		2.32		*p*	1.23	*p*
Topaz	0.62		0.34			
Apatite						*p*
Titanite				*p*		
Epidote (?)						*p*
Beryl				*p*		
Hematite						*p*
Limonite		*p*	*p*	*p*	*p*	
	100.01	100.01	100.03		100.00	99.96

p = present in thin section.

1*br*. Monzogranite (Alaskose)

2*r*. Alaskite (Liparose)

3*br*. Porphyritic leucomonzogranite (I.4.4.3)

4*r*. Pegmatite

5*r*. Leucogranite

6*r*. Leucogranitic aplite (Liparose)

granite, beryl-bearing pegmatite, leucogranite, leucogranitic aplite, and an acid dike rock. Chemical analyses of monzogranite, porphyritic leucomonzogranite, alaskite, and leucogranitic aplite have been recorded.[10] Table II gives the minerals and quantitative measure-

[9] Albert Johannsen, *A Descriptive Petrography of the Igneous Rocks*, Vol. I (University of Chicago Press, 1931), pp. 154–55.

[10] Stewart, *op. cit.*

ments of the constituents of the specimens. The presence of fluorite and topaz in the majority of the thin sections indicates pneumatolytic action. The plagioclase in the rocks varies in composition from $Ab_{97}An_3$ to $Ab_{93}An_7$. Microperthite is noted in four of the six thin sections.

COMPARISONS WITH ROCKS OF OTHER AREAS

One of the outstanding questions of Antarctic geology and petrography is whether the rocks of King Edward VII Land are similar to those of East or West Antarctica. Schetelig,[11] after a study of thin sections of the rocks from Scott's Nunatak, King Edward VII Land, and those of Mount Betty, Queen Maud Mountains, South Victoria Land, arrived at the conclusion that the ordinary granites from the two localities are identical. After a comparative study of granite, diorite, and granodiorite from Graham Land with the Scott's Nunatak specimens, he concluded that the rocks of these two regions are not similar. Bodman[12] examined Amundsen's specimens and found that they possessed characteristics different from those of the rocks of the Antarctic Archipelago. He states: "Meine Auffassung bleibt daher die, dass die Gesteine aus dem Grahamgebiete einerseits und aus Edward VII Land mit Süd-Victoria Land anderseits von ganz verschiedenen Typen sind."

After comparative petrographical studies of Gould's specimens from King Edward VII Land with specimens from the Queen Maud Mountains of South Victoria Land and with rocks collected in the Antarctic Archipelago by the Expédition Antarctique Française, 1903–5, it is concluded that the rocks of the Rockefeller Mountains have close affinities with the high sodium- and potassium-bearing rocks of East Antarctica, and show little affinity with the high calcium-, magnesium-, and iron-bearing rocks of the Andes of South America and the Antarctic Archipelago.

[11] *Op. cit.*

[12] Gösta Bodman, "Petrographische Studien über einige antarktische gesteine," *Wissenschaftliche Ergebnisse der Schwedischen Südpolar-Expedition, 1901–03, Geologie und Paläontologie*, Vol. III, Part 15 (1916), pp. 76–79.

REVIEWS

The Eskers and Terraces in the Basin of the River Susaa and Their Evidences of the Process of the Ice Waning. By S. A. ANDERSEN. Danish Geol. Surv., II Raekke, Nr. 54, 1931.

From a detailed study of the eskers and terraces it is concluded that the peripheral portion of the ice sheet became stagnant while that behind

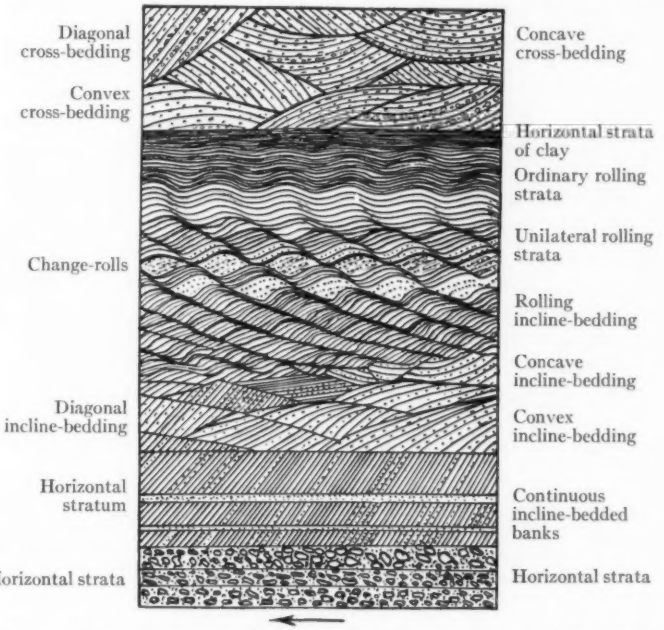


FIG. 38.—Schematic reproduction of the most important forms of structure in stratified gravel, sand, and clay. The arrow indicates the direction of the meltwater stream that laid down the deposits under the horizontal strata of clay, which indicates a winter-deposit; over this the stream has run at right angles to the section shown.

continued to move, shearing upon and crowding against the dead ice. The line of junction between the living and dead ice is called the "winter line," and along this line "winter moraines" were pushed up. During

each winter this line remained stationary but during each summer it moved inward, extending the area of dead ice. Commonly it would move a mile or more during a summer. This concept elucidates the alpha and beta layers of the esker—long a puzzle; the latter having been deposited just before the ice became stagnant and still could crowd and distort the layers, the former after stagnation was complete and no distortion took place. A water table became established in the dead ice, above which fluvioglacial material was not deposited.

What seems to be the first fairly complete classification of cross bedding is included in the report and is brought to the attention of the reader for its general interest. The accompanying diagram of Andersen (Fig. 38) is self-explanatory when it is pointed out that it is arranged in order of increasing transporting power of running water from "horizontal strata of clay" downward to the base of the diagram. The reviewer calls attention to Andersen's limitation of the term "cross bedding" to the structures seen in section normal to the direction of the stream flow. In many respects it seems unfortunate that a general term should be thus restricted. It might have been better to call all the structures shown in the diagram "cross bedding" and to give a specific name to the type at the top of the diagram.

PAUL MACCLINTOCK

Kohlensäure und Kalk. By JULIUS PIA. "Die Binnengewässer" (a series of monographs on limnology and related topics edited by A. THIENEMANN), Vol. XIII. Stuttgart: E. Schweizerbart'sche Verlagsbuchhandlung, 1933. Pp. vii+183; figs. 17, pls. 3, tables 58. Paper, RM. 21; bound, RM. 22.50.

The present volume, covering carbon dioxide and chalk, is divided into three main sections. The first part, comprising about half the volume, discusses the underlying principles of the solubility of calcium carbonate. The author first defines and distinguishes the meanings of the terms "solubility," "concentration," etc., and after these preliminaries enters into the theory of the solubility of calcium carbonate. Earlier and current works are comprehensively reviewed, and three theories are discussed: the molecular, the dissociation, and the activity theories. The presentation of the theoretical factors is followed by a consideration of the effects of temperature, pressure, particle size, and the like, on the solubility. The last half of the section is devoted to numerical values of the solubilities of carbon dioxide and calcium carbonate under various circumstances. This part is illustrated with numerous tables and graphs.

The second main division of the volume considers the precipitation of chalk. Here are discussed abiogenic, plant, and animal agencies that cause deposition. The effects of temperature changes, the reduction of the carbon dioxide content of the water, etc., are included under the first heading. Among the biogenic causes are included the physiologic processes of plants, which may involve the removal of carbon dioxide from the water or from calcium bicarbonate, thus causing the precipitation of chalk. Bacterial and animal agencies are also discussed in some detail.

The third part of the monograph contains a classification of chalk deposits, including those formed in hot springs, flowing waters, fresh-water lakes, and salt lakes. A summary at the end of the section indicates that in flowing streams the deposition of chalk is largely chemical; in fresh-water lakes it is mainly from the physiological processes of plants; but in salt lakes a variety of causes is manifest.

The book as a whole is rich in material for sedimentary petrologists interested in chalk deposits. The first part will appeal to those interested in the physical setup for carbonate solubility, and the second and third parts to those interested in mechanisms of deposition or in genetic classification. The complete Bibliography, occupying more than twenty-five pages, attests to the research involved in preparing the monograph. The author has performed an important function in co-ordinating several fields of research into a compact but comprehensive treatise on the subject.

W. C. KRUMBEIN

The Unstable Earth. By J. A. STEERS. New York: E. P. Dutton & Co., 1932. Pp. 341; maps and diagrams 66. $4.50.

The stated purpose of the book is to review for geographers and physiographers some of the major problems of geomorphology. The material is, therefore, descriptive and no new theories or explanations are advanced.

The opening chapter describes the larger structural features of the earth's surface—the continents, oceans, and mountain systems. An accompanying map showing trend lines of the various mountain systems would have aided the reader greatly in following the descriptions.

Chapter ii presents a brief discussion of the constitution of the earth in accordance with seismological evidence and isostatic measurements.

Chapter iii treats of the structure of the European pre-Cambrian, Caledonian, Variscan, and Alpine mountain systems. The Appalachian

and Laramide deformations in North America are, however, dismissed with very few lines. To an American reader this seems unfortunate in view of their importance and the amount of available data.

Chapter iv is devoted to recent theories which are well summarized. The following are considered: the planetesimal hypothesis of Chamberlin, the geosynclinal-orogen theory of Kober, the thermal-contraction theory revived by Jeffreys, the drift theory of Wegener, the theory of radioactivity of Joly, the hypothesis of sliding continents of Daly, and the convection-current theory of Holmes. The author's sweeping statement that the planetesimal hypothesis has now been "exploded" is certainly in need of revision. It has been attacked, as any theory may be, but many able scientists today are supporters of this hypothesis. For reference the reader is directed to only Chamberlin and Salisbury, *Geology*, Volume II (1909), and more important works appearing as much as twenty years later have been omitted.

The two concluding chapters deal with the mobility of the earth in recent time. Coral reefs and coral islands are especially well described. It seems to the reviewer, however, that much of the material presented has little direct bearing on the mobility of the earth, but on the whole the work has been well done and the book should find wide use among geologists and geographers.

W. TANSLEY

Paleolithic Man and the Nile Valley in Nubia and Upper Egypt. By K. S. SANDFORD and W. J. ARKELL. "Oriental Institute (University of Chicago) Publications," Vol. XVII, *Prehistoric Survey of Egypt and Western Asia*, Vol. II. Chicago: University of Chicago Press, 1933. Pp. xvii+92; pls. 43; map 1. $6.00.

The first volume of this series treated of the geology and archaeology of the Faiyum region; the present work covers Egypt from the Second Cataract to Luxor; it is hoped in subsequent volumes to complete the survey northward to the Mediterranean. An account is given of the deposits from Pliocene to Recent times along several hundred miles of the Nile Valley, and of such stone implements as are found in these sediments.

The authors find no evidence of human occupation older than a 100-foot terrace, where Chellean implements are found. Acheulean finds pertain to a 50-foot terrace. Mousterian man is represented on 30- and 10-foot terraces. During Mousterian times the evidence indicates the oncoming of arid conditions, first in Nubia, then in Upper Egypt. It appears

significant that the typical Upper Paleolithic cultures of Europe are not present; in their place we find the Early and Middle Sebilian, of Mousterian ancestry, followed by a "neanthropic" Capsian, indicating a migration, very probably from the west.

There is no more interesting problem in early human history than the correlation of the final stages of the older (and western) lithic industries with the historic civilizations of the Near East. The Oriental Institute is to be congratulated for the initiation of this series of investigations which constitute the first organized attack on this problem.

A. S. ROMER

A Revision of the Ceratopsia or Horned Dinosaurs. By RICHARD SWAN LULL. New Haven: "Memoirs Peabody Museum," Vol. III, Part 3, 1933. Pp. xii+175; figs. 42; pls. 17. $4.00.

The original certatopsian monograph published some three decades ago gave an adequate account of such few members of this interesting group as then had been discovered. Since that time our knowledge of horned dinosaurs has been vastly increased, and up-to-date summary has been badly needed. The present revision is thus exceedingly welcome. It is appropriate that the author of this excellent work should be Dr. Lull, who brought the 1907 monograph to completion and has retained his interest in the group through the intervening years.

Useful basic data are presented in brief sections dealing with the history of discovery and geologic and geographic distribution. Suggestions are made regarding the habits of these strange animals. A general account of ceratopsian anatomy, based mainly on *Monoclonius*, occupies a third of the text; the final half of the work is a systematic description of genera and species. Of interest among the illustrations are flesh restorations of *Monoclonius* by Lull and of *Chasmosaurus* by Russell.

A. S. R.

Man Created during Descent. By REV. MORRIS MORRIS. London: Marshall Bros., 1926. Pp. 111. 3/6*s*.

One more in the long series of attempts to reconcile Genesis with paleontology and archeology. The author believes in the descent of man from lower forms by "a continuous process which has been punctuated by discontinuous acts of creation, the last of which took place in the first man not more than five or seven dozen centuries ago, while he was being 'formed' in his mother's womb." "Man and Civilization entered the world together at the beginning of the New Stone Age." The argument is based

on the seemingly sharp cultural gap between the paleolithic and neolithic —a gap, however, which is becoming less marked with increasing knowledge.

A. S. R.

The World of Fossils. By CARROLL LANE FENTON. Appleton's "New World of Science Series." New York: D. Appleton–Century Co., 1933. Pp. x+183; figs. 35. $2.00.

This is another of the excellent small, "popular" volumes which are being issued under the editorship of Watson Davis as a part of Appleton's "New World of Science Series." Written by an invertebrate paleontologist, the book does, as the author says, "range far beyond" his own researches. Yet it contains many an interesting bit of historical information concerning fossils which should not only intrigue the intelligent layman, but which probably will enlarge the experience of a number of specialists.

Dr. Fenton has chosen to regard fossils "as the remains of living organisms which had work to do, problems to solve and emergencies to meet." With this viewpoint constantly in mind the author has been able to create for the reader a series of reasonably representative dramas of the life of the past. If the discussion occasionally takes on a slightly teleological aspect, this minor defect is overweighed by the increased animation of the resulting descriptions. Most of the chapters have stimulating titles, such as "Hunting Big Game of the Past," "Birds That Had Teeth," "Can These Bones Live," and "Death on a Delta." The text has also been enlivened by thirty-five pen sketches by the author.

The publication of this volume, together with the relatively recent appearance of Lull's booklet, *Fossils*, at last makes it possible for the educated non-geologist to get a fairly complete picture of the hosts of interesting organisms which preceded modern man as temporary rulers of this earth.

C. C.

The Geology of the Rove Formation and Associated Intrusives in Northeastern Minnesota. By F. F. GROUT and G. M. SCHWARTZ. Minnesota Geological Survey Bulletin 24. Minneapolis: University of Minnesota Press, 1933. Pp. xi+103; figs. 44; pls. 20. $2.00.

The Minnesota area of Rove slate is a narrow strip south of the international boundary from Pigeon Point on Lake Superior to a few miles west of Gunflint Lake in Cook County, a total distance of about 62 miles. The bedrock of this area includes some pre-Animikie formations of very

limited exposure, the Animikie, and the Keweenawan. The Animikie series has a lower member, the Gunflint iron-bearing formation, and an upper member, the Rove slate, which is in reality thin-bedded argillite and graywacke with a minor amount of quartzite. The Keweenawan consists of a few, thin clastic sediments and bedded lava flows together with the Logan diabase dikes and sills and the Duluth gabbro mass.

The structure is a simple homocline with south dip, generally 4°–15°, modified by a very subordinate amount of faulting and almost no folding. Differential erosion of the tilted Rove slates and interleaved sills gives rise to the present topography, the "sawtooth mountains."

The report contains 15 contoured outcrop maps, 4 plates of cross sections, and a composite 3-color geologic map.

Of special interest is the description of the Logan sills, the larger ones of which contain anorthosite inclusions, and a restudy of the classic Pigeon Point composite sill. The authors conclude that the granitic "red rock" of the latter developed at a late stage by differentiation through crystal settling and not by assimilation of quartzite by the parent diabase magma, whereas the included anorthosite formed at an early stage by a rise of the feldspar crystals which collected in masses near the top of the sill. The main body of this sill is gabbro.

A short treatment of the economic geology, mainly a description of silver prospects (calcite-barite-sulphide veins), is included in the text.

F. J. PETTIJOHN

Physics of the Earth. VI, *Seismology.* By the Subsidiary Committee on Seismology. "Bulletin of the National Research Council," No. 90. Washington, D.C.: National Research Council, 1933. Pp. viii +223. Paper $2.00; cloth $2.50.

This volume, containing contributions by five members of the Subsidiary Committee on Seismology, treats the subject of seismology in an introductory fashion such that the book will be of value to the student and to the worker in other fields. It is perhaps inevitable that the simplicity and completeness of the discussion vary in the different chapters. This is partly due to the necessary mathematical treatment of certain phases of the subject and to the limitations of space imposed upon phases which would require too detailed statement or analysis to permit uniform treatment.

The first ten chapters are of great interest from the geological point of view. After introductory definitions and classifications of earthquakes, J. B. Macelwane describes the origin of tectonic, plutonic, and impact earthquakes. The latter type is dismissed as not important or perhaps

even almost non-existent from natural causes. The chapter on volcanic earthquakes by H. O. Wood is the longest in which causes are discussed, but most of the chapter is devoted to emphasizing the importance of the tectonic origin of many earthquakes which occur in volcanic regions and which therefore might be considered to be volcanic in origin. In many instances it is difficult to determine the ultimate cause.

The longest chapter is devoted to field investigations of earthquakes and emphasizes the limitations and problems of such work. This chapter and the following one, on intensity and surface geology, are by H. O. Wood. Of the next three, by H. F. Reid, two are short and deal with the magnetic effects attributed to earthquakes, and with the conception of the focus; the other gives an excellent outline of the elastic rebound theory of earthquakes.

The last ten chapters of the book are of less interest to the geologist. This is particularly true of the mathematical analyses of earthquake waves by J. B. Macelwane. J. A. Anderson gives a lucid statement of the principles of the seismograph and of the problems involved in the selection of the proper types for different purposes. The interpretation of seismograms and of travel-time curves for both near and distant earthquakes is satisfactorily summarized by Perry Byerly. The short concluding chapter on seismic geography is by the same writer.

EDWARD L. TULLIS

The Principles and Practice of Geophysical Surveying. Report of the Imperial Geophysical Experimental Survey. Edited by A. B. BROUGHTON EDGE and T. H. LABY. Cambridge: University Press, 1932. Pp. xi+372.

The experimental work upon which this volume is based was carried out in Australia in 1928, 1929, and 1930, under the auspices of the British Empire Marketing Board and the Commonwealth Government. The purpose of the survey was to determine the applicability of various geophysical methods where geologic conditions were already known.

The volume is divided into two parts: the first devoted to the individual surveys and conclusions; the second dealing almost exclusively with theories and descriptions of instruments and their application to field conditions. In both parts the electrical methods receive by far the major attention, though other methods are well discussed. This distribution is not intended to disparage other methods, but is rather the result of the conditions of the survey and the paucity of literature upon electrical prospecting.

The first part is intended more for the general reader than for the

specialist in geophysical prospecting and may be understood without the aid of more than high-school mathematics and physics. The second part is more detailed and theoretical, though even here the mathematical and physical requirements are by no means great.

The volume is a welcome addition to the rather meager list of reference books in English upon the subject of applied geophysics.

H. W. STRALEY, III

Kyanite in Virginia. By ANNA I. JONAS and JOEL H. WATKINS. Virginia Geological Survey, Bulletin 38. University, Va., 1932. Pp. xi+47; figs 1; pls. 11; table 1.

Kyanite is an aluminum silicate which, like sillimanite and andalusite, having the same composition, has of recent years found large use in the manufacture of the porcelain parts of spark plugs.

Kyanite is found in central Virginia as a component of the pre-Cambrian metamorphic Wissahickon formation and in southwestern Virginia in pegmatites. The Wissahickon formation in the kyanite area has been dynamo-metamorphosed at two different periods. There is no evidence that igneous metamorphism by the intrusive granites is responsible for the kyanite, for it is not restricted to contact zones. The kyanite content in the Baker Mountain area where the principal development has occurred ranges from 20 to 80 per cent with an average of over 30 per cent.

The report describes fully the petrography of the kyanite-bearing and associated rocks.

E. S. B.

The Marble Industry of Vermont. By G. H. PERKINS. Report of the State Geologist on the Mineral Industries and Geology of Vermont, 1931–32. Pp. 315.

This is the first state report on the Vermont marble industry to be issued in twenty years. The general properties of Vermont marbles are very briefly treated. Fossils are exceedingly rare, but the presence of Maclurites in calcite marble in Rutland and several other localities in western Vermont indicates an Ordovician age. Dikes of dark-colored volcanic rock from a few inches to 25 feet wide occasionally traverse the marble. Sixteen pages are devoted to the history of the marble industry. The remainder of the report is devoted mainly to descriptions of individual quarries, to brief characterizations of the many trade varieties, and to description of the machines and methods used in quarrying and finishing the stone.

E. S. B.

Geology of Coral Reefs. By Dr. PH. H. KUENEN. The Snellius Expedition in the Eastern Part of the Netherlands East-Indies, 1929–1930, Vol. V, Part 2. Utrect: Kemink en Zoon N.V., 1933. Pp. 126; figs. 106; pls. XI.

Although not intended to be an exhaustive study either of the East Indian reefs or of the coral-reef problem as a whole, this report, nevertheless, adds much to our knowledge of reefs and their method of formation. It merits careful study by all geologists interested in coral-reef problems. In the main the report extends and confirms the earlier work of Umbgrove, although the author differs from him on some points.

Chapter i is a short introduction and very brief résumé of the views of previous workers. Chapter ii, forming with chapter vi the main body of the work, consists of descriptions and illustrations of the thirty-one reefs or groups of reefs visited. Chapter iii records briefly some observations of coral growth. Chapter iv discusses movements of the reefs relative to sea level. Two important points are made: first, three possible eustatic levels at $\frac{1}{2}$–1, $1\frac{1}{2}$–2, and 4–5 meters were observed; second, geological evidence seemed to indicate that solution by sea water is limited to the tidal range. In chapter v various phenomena of reef flats are discussed. Chapter vi is a discussion of the formation of atolls. Practically all of the evidence discovered is in favor of Darwin's theory combined with the theory of glacial control in the manner suggested by Davis. The author shows conclusively that the Toekang Besi Islands could not be formed by glacial control alone. He also shows that the steep slopes of coral reefs to a depth of several hundred meters are not in accord with the glacial-control theory. The chapter ends with a summary of twenty points which are apparently contradictory to the theory of glacial control. Chapter vii is a short summary of the principal results.

GORDON RITTENHOUSE

General Bulletin Handbook (*Minerals Division*). Bulletin No. 22. New Orleans: Published by State of Louisiana Department of Conservation, 1933. Pp. 345.

This *Bulletin* contains several separate discussions: "Salt-Dome Possibilities," by R. A. Steinmayer; "A Brief Survey of the Mineral Resources of Louisiana," by J. A. Shaw; "Foraminifera of the Jackson Eocene at Danville Landing on the Ouachita Catahoula Parish, Louisiana," by H. V. Howe and W. E. Wallace; and "A List of Some of the Available Publications Dealing with the Geology and Mineral Resources of Louisiana and Related Areas."

R. T. C.